Radiation Hardness Assurance Issues for JPL Spacecraft Microelectronics

Chuck Barnes and Allan Johnston
Jet Propulsion Laboratory
California Institute of Technology
charles.e.barnes@jpl.nasa.gov
(818) 354-4467

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Outline

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- **Summary of radiation effects**
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- **Summary of major radiation issues**
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- **Technical examples**
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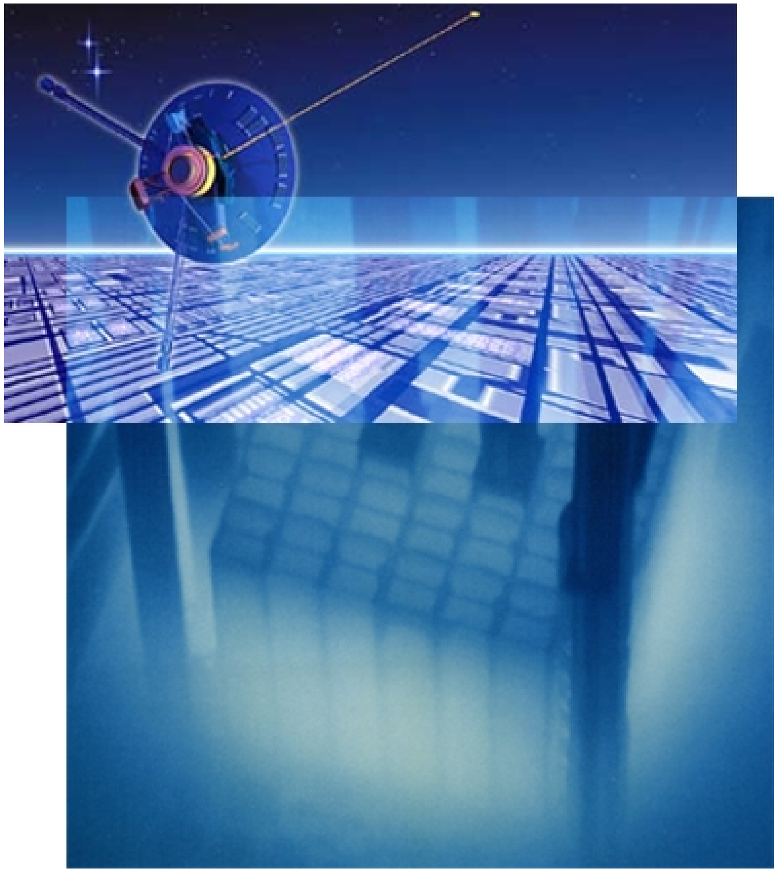
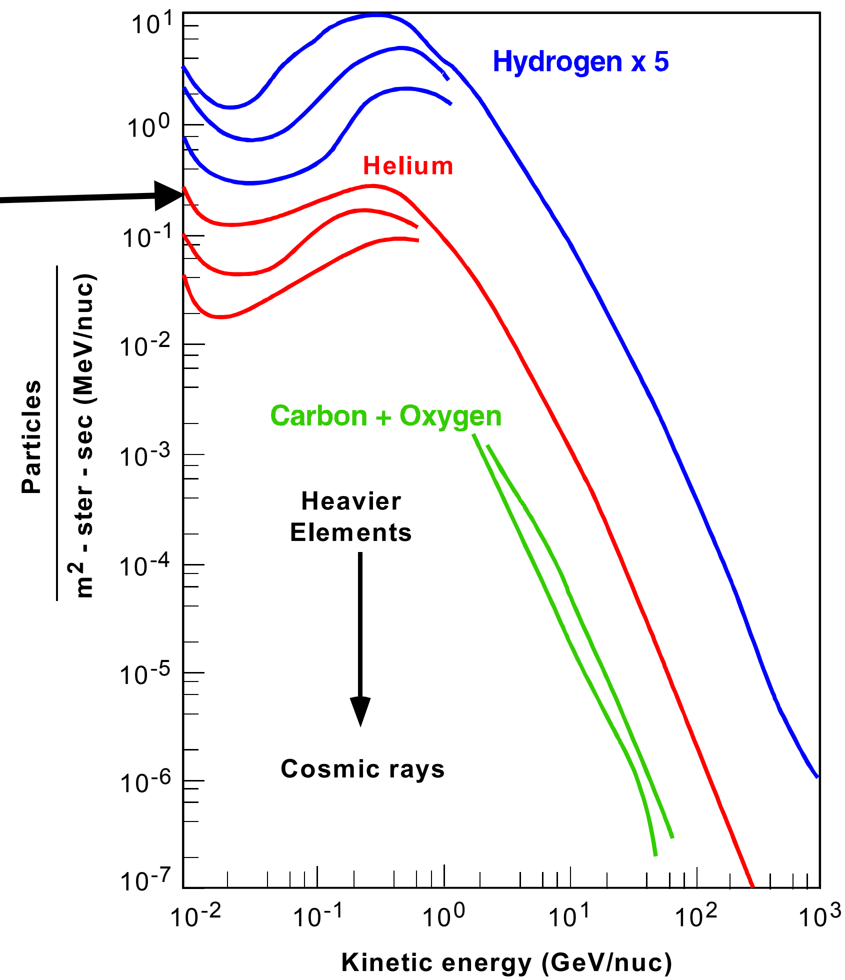
  - Displacement damage - a “new” old problem
    - Optocoupler failures on TOPEX/Poseidon
  - Flash Memories
- **Future trends**
  - Scaling effects
  - Radiation “rules of thumb”

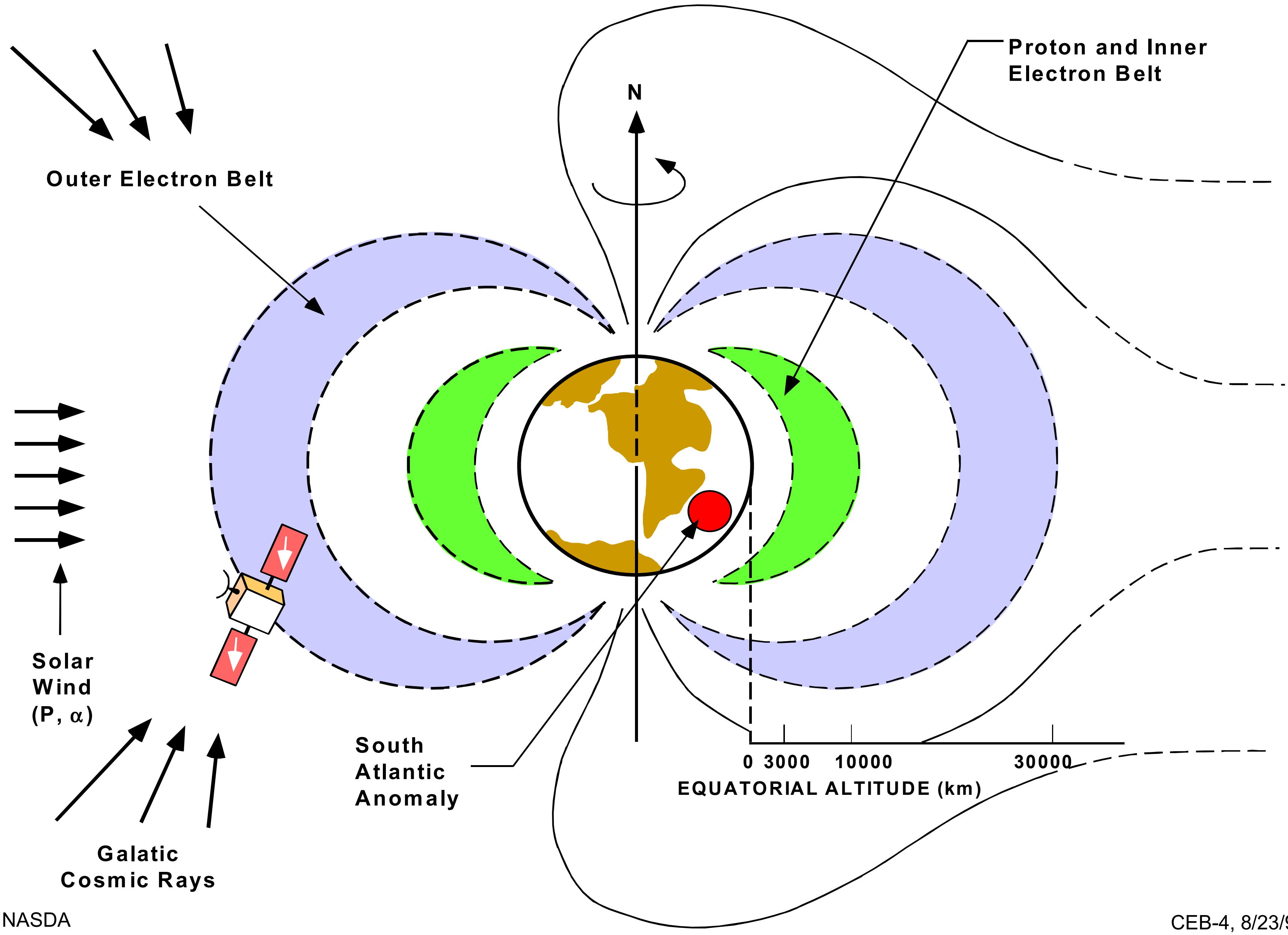


Sources of Space Radiation

- **Earth's Van Allen belts**
  - Discovered in 1958 by Explorer 1
  - Electrons, protons trapped in Earth's magnetic field – 1000 to 6000 km
    - South Atlantic Anomaly (SAA) – particles down to about 100 km - similar to Mars atmosphere
- **Galactic cosmic rays (GCRs)**
  - Energetic (100s of MeV) ions up to about iron
  - Can have hardened GCR spectrum at Mars surface
- **Solar flares**
  - Intense bursts of protons, electrons, heavier ions
  - Solar flares severe in 1989 – 1991
  - Results in "pumping up" of Van Allen belts
  - Extensive damage to in-flight spacecraft/satellites
  - Also problem for Mars orbiting and surface systems
- **Environments around other planets**
  - Sulfur, oxygen near Jupiter due to volcanic action on Io
- **Man made sources**
  - Radioisotope Thermoelectric Generators (RTGs), space reactors
  - Secondary reactions in shielding



Sources of Radiation Near Earth



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Summary of Important Radiation Effects

Type of Radiation Effect

- **Total Ionizing Dose (TID) – protons, electrons, gamma rays**
  - Enhanced low dose rate effect
- **Single Event Effects (SEE) – protons, heavy ions**
  - Single Event Upset (SEU)
  - Single Event Latchup (SEL)
  - Single Event Functionality Interrupt (SEFI)
  - Single Event Burnout (SEB) and Gate Rupture (SEGR)
  - Single Event Dielectric Rupture (SEDR)
- **Displacement damage effects – protons, neutrons**
- **Single particle "microdose" – heavy ions**
- **Single particle-induced transients in linear/analog parts**

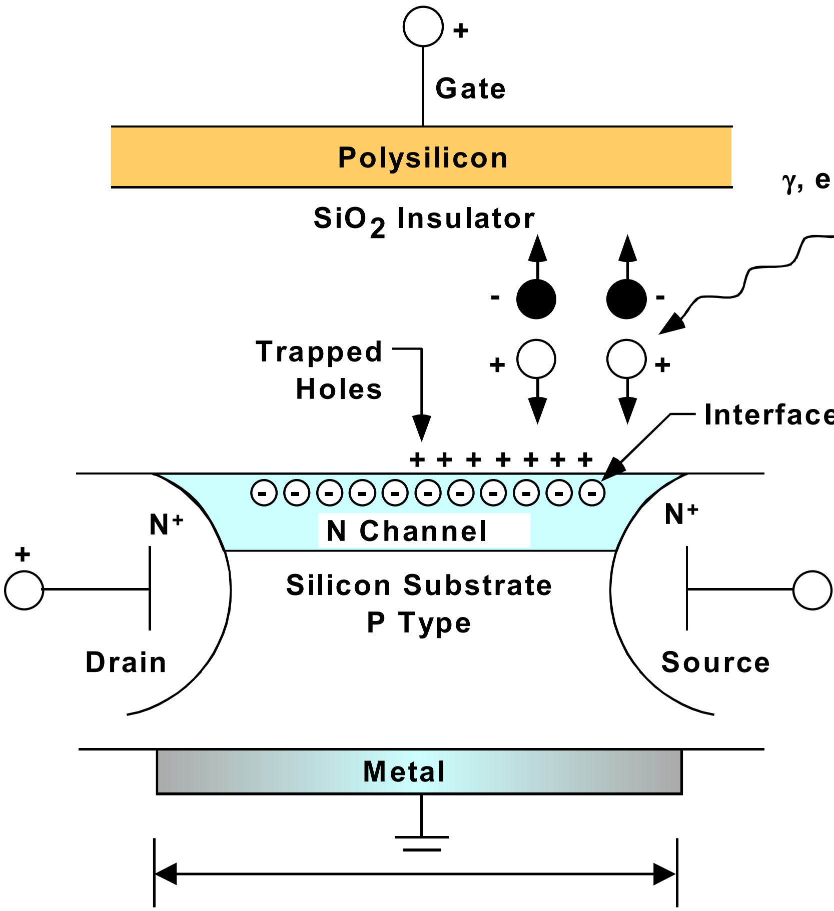
Effect on Devices

- **Both gradual, parametric degradation and sudden functional failure – cumulative effect**
  - Severe RHA problem in linear bipolar devices
- **Variety of single particle effects**
  - Soft failures – change in logic state
  - Functional and catastrophic failure
  - Recoverable functional failure; change in operating mode
  - Catastrophic failure in power transistors
  - "Hard" SEUs; similar to SEGR, FPGA anti-fuse shorting
- **Bulk lattice damage – "billiard ball" collisions**
  - Analog devices, solar cells, optocouplers
- **TID failure of a single transistor – "weak" bits**
- **Large transient that can upset following digital circuits**

Total Ionizing Dose (TID) Effects in Microelectronics

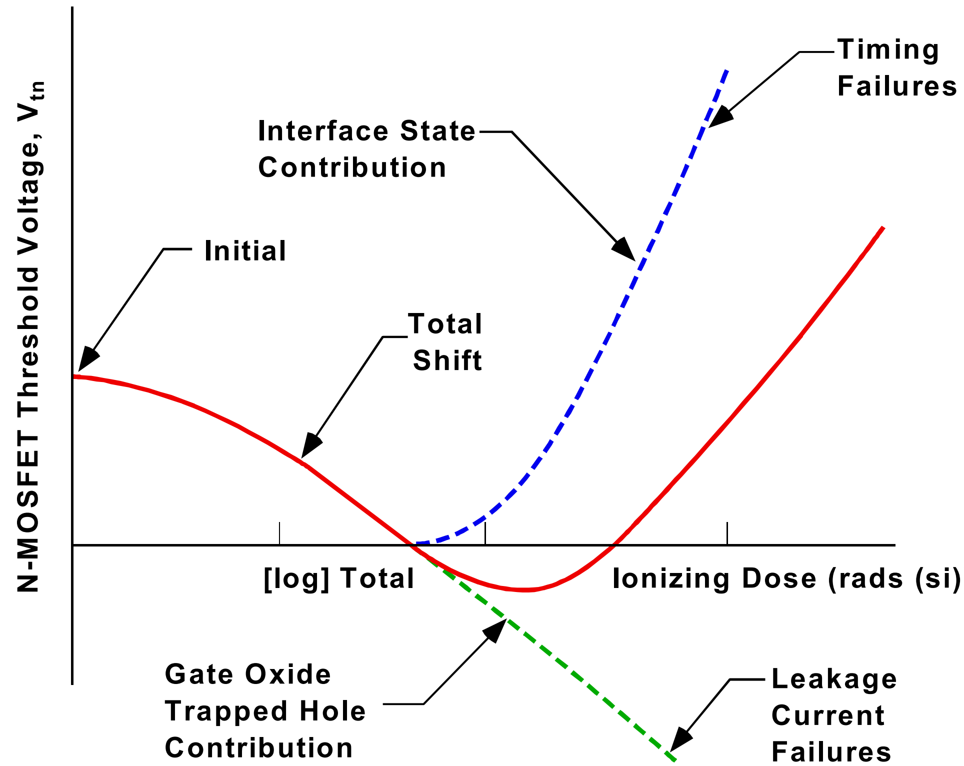
- **Most important in Metal-Oxide-Semiconductor (MOS) Si digital and analog devices and circuits**
  - Si - SiO2 interface is where damage accumulates
  - In modern commercial circuits, field oxides used to isolate devices from each other in circuit are sensitive and more of a problem than gate oxides
- **Circuit response to radiation depends on nearly all external and internal parameters**
  - Fabrication process characteristics, especially oxide growth methods
  - Temperature, bias during irradiation, dynamic or static bias, dose rate
- **Damage annealing takes place during and after exposure to radiation**
  - Different failure mechanisms can occur during annealing period
- **Cobalt-60 traditionally used as radiation test source**
- **Usually need to determine both parametric variation and functional failure**
- **Shielding is effective up to a point**
  - Small, mass-constrained spacecraft like Europa cannot allow much shielding
- **Commercial devices can fail at very low doses, in the range of ISS requirements**
- **Enhanced low dose rate effect (ELDR) in bipolar and BiCMOS devices is difficult hardness assurance problem**
  - Actual environment in more of a risk than test environment

Effect of Ionizing Radiation on Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)



In a Pentium II processor this dimension is about 0.35 µm

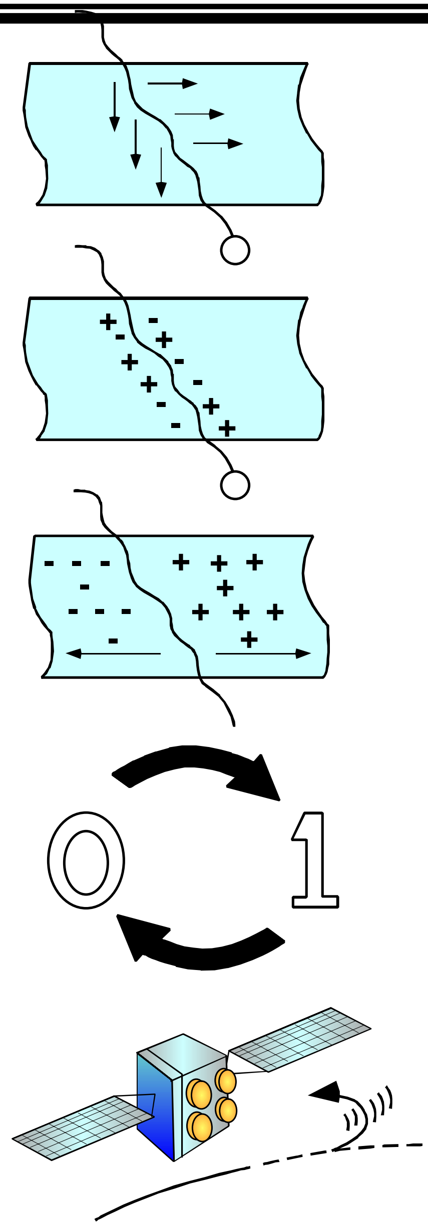
Radiation response of modern commercial Si digital circuits, such as a Pentium II processor, can be very complex because of dependence on nearly all internal (process) and external parameters



Single Event Effects (SEE) in Microelectronics

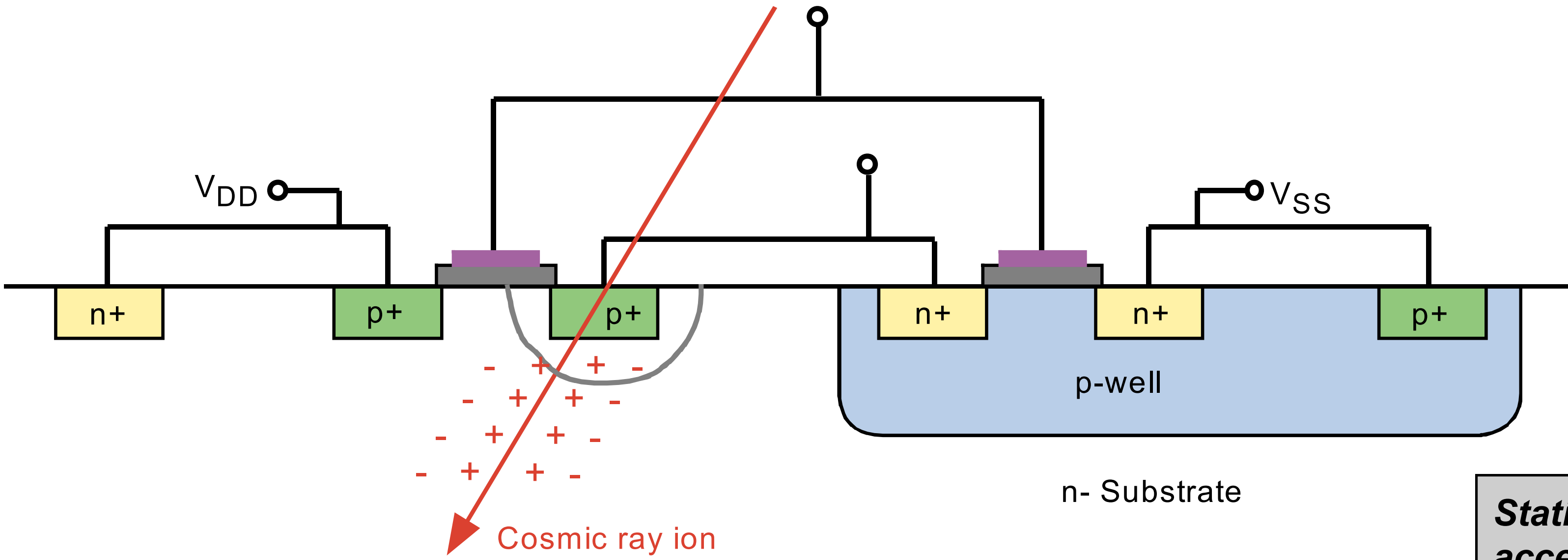
- **Caused by energetic heavy ions and protons**
- **A single ion deposits dense track of charge in a circuit element**
- **As noted earlier, there are several different SEEs**
    - Transient or non-permanent
        - Single event upsets (SEUs)
        - Single event transients (SETs)
        - Single event functionality interrupt (SEFI) - may require power cycling
    - Permanent, sometimes catastrophic
        - Single event latchup (SEL) - can be destructive
        - Single event gate rupture (SEGR), also more generally referred to as dielectric rupture (SEDR)
        - Single event burnout (SEB)
- **Important parameters**
    - Cross section for given effect
        - Sometimes larger than chip area
    - Linear energy transfer (LET)
        - Rate of deposition of ionizing energy/unit length by particle in device/circuit
    - Temperature, especially for latchup
    - Upset rate - convolution of particle distribution for mission and cross section data
- **Thresholds exist for most of these effects**
    - Very desirable to stay above proton LET threshold
- **Shielding is not very effective and can make things worse**

Single Event Upset (SEU) Sequence of Events



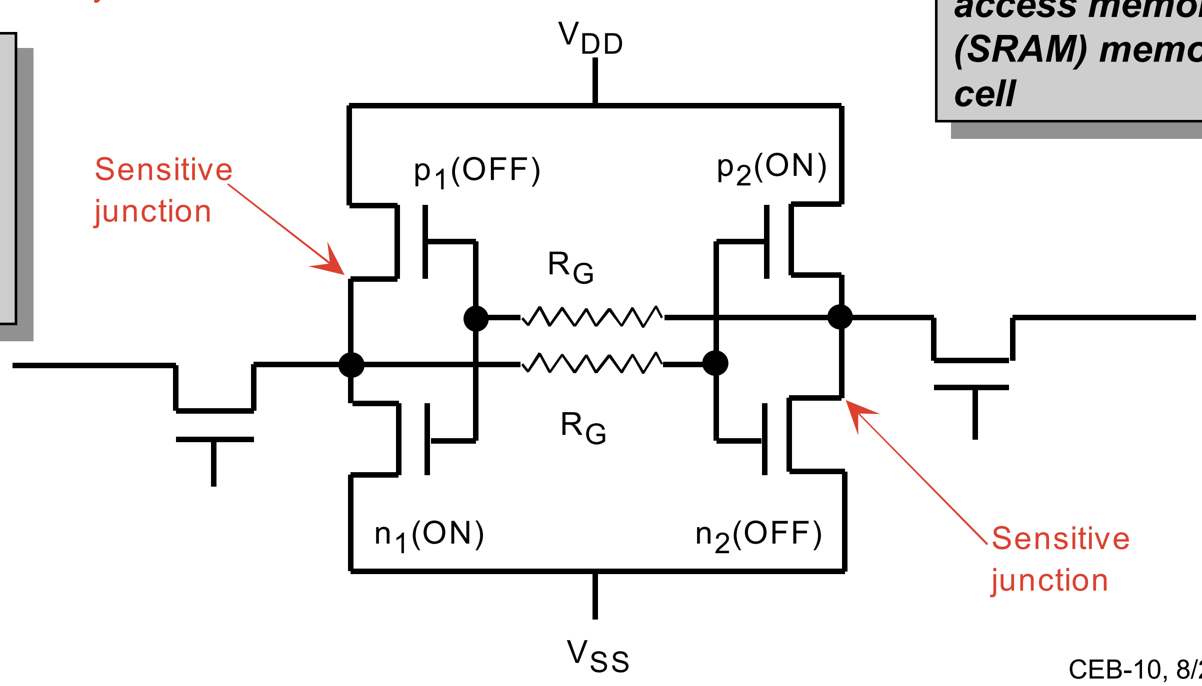
- Incident Charge Particles Lose Energy Through Ionization
- Ionization Creates Electron/hole Pairs
- Freed Electrons And Holes Are Collected Within A Circuit
- Logic State Of Circuit Toggles Erroneously
- Spacecraft Suddenly Performs "Unscheduled" Maneuver

Single Event Upset (SEU) Mechanism

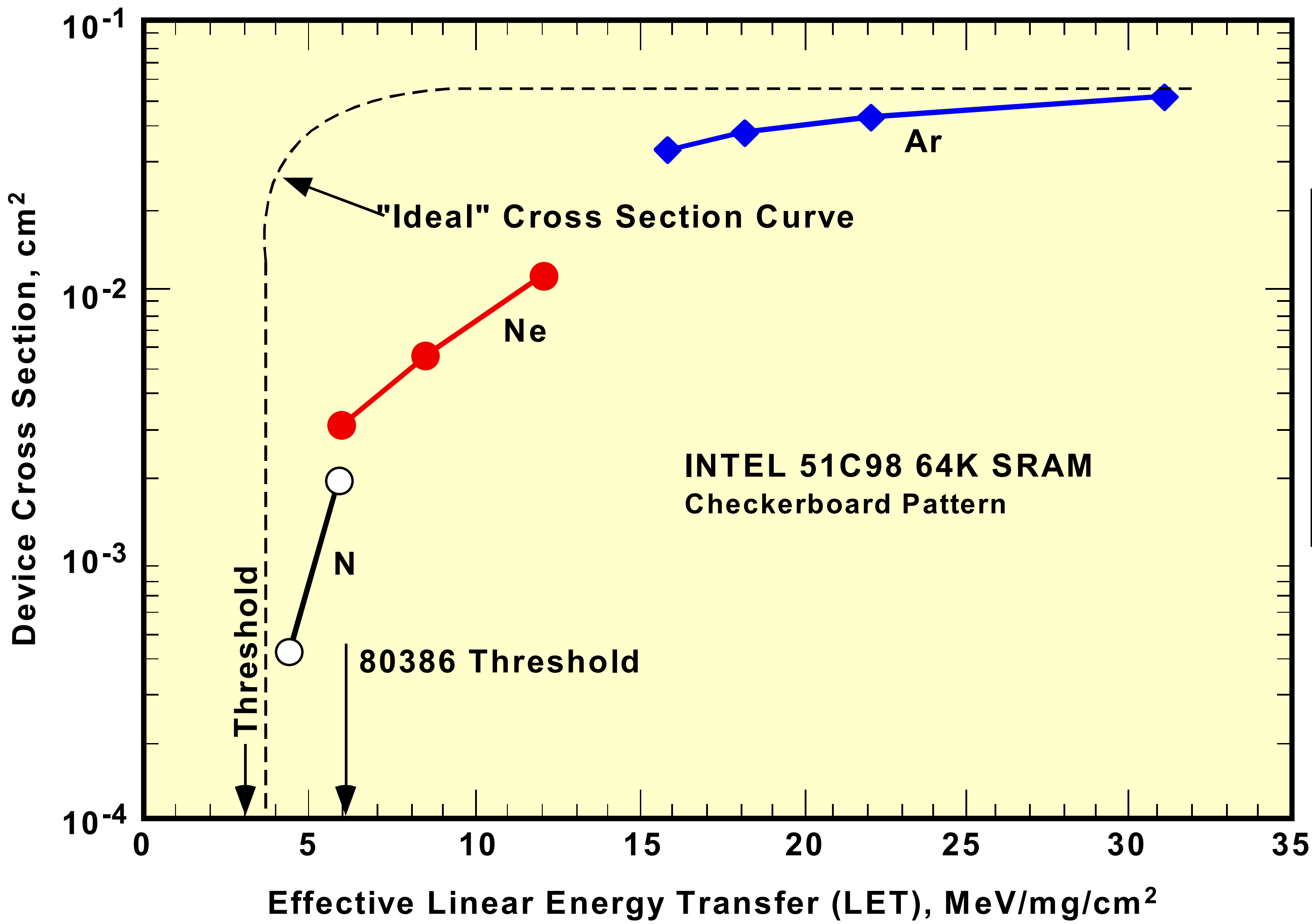


If deposited ionizing energy creates collected charge that exceeds critical charge for transistor turn-on, memory cell will upset and change logic state

Static random access memory (SRAM) memory cell



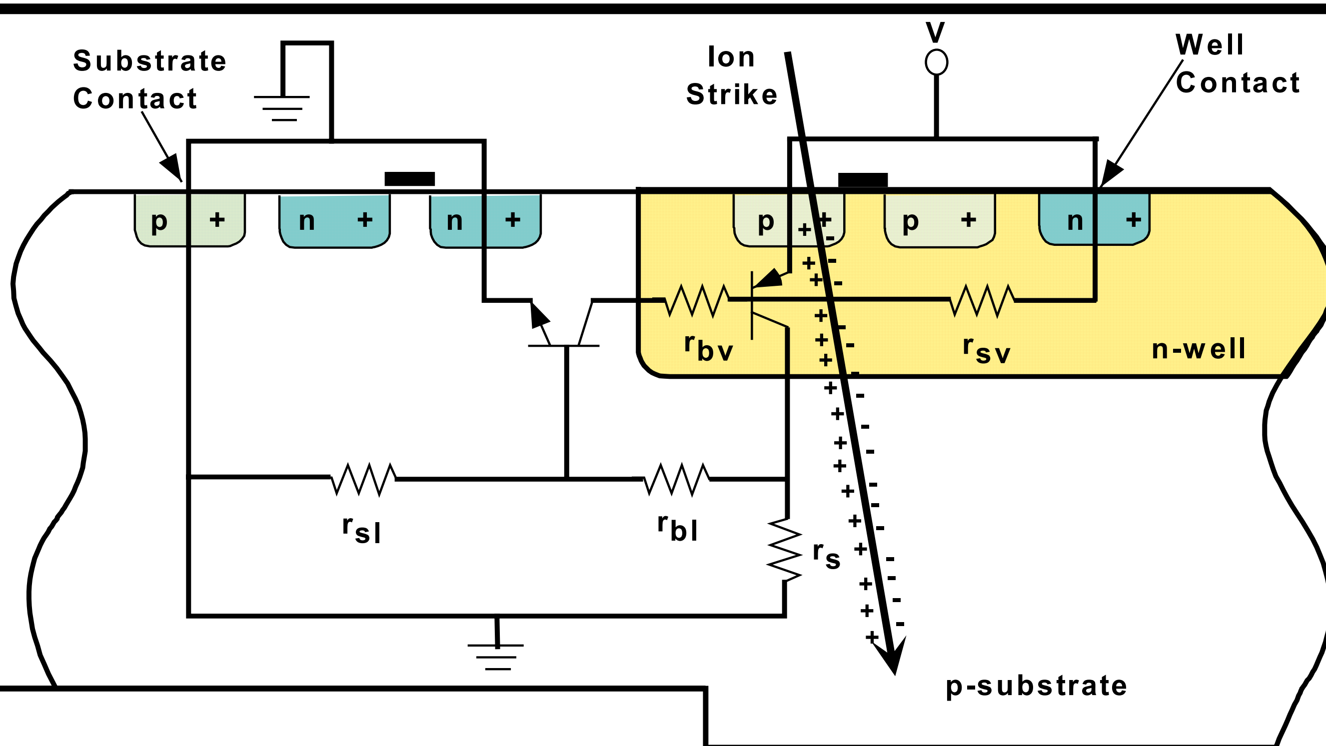
Typical Single Event Upset (SEU) Data

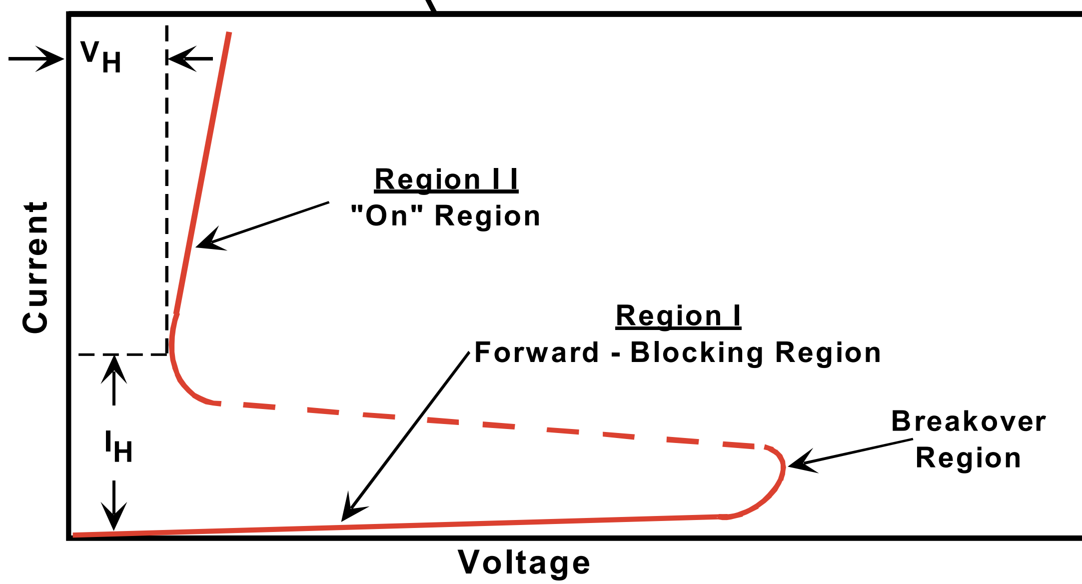


For a sensitive device, such as a large commercial DRAM, the SEU cross section can be larger than the chip area due to multiple upsets

Single Event Latchup (SEL)

- Existence of parasitic vertical and horizontal bipolar transistors (*p-n-p-n*) allows regenerative structure to exist and makes circuit susceptible to latchup
- When the product of the gains of these transistors is greater than 1, an SCR-like action takes place and latchup can occur





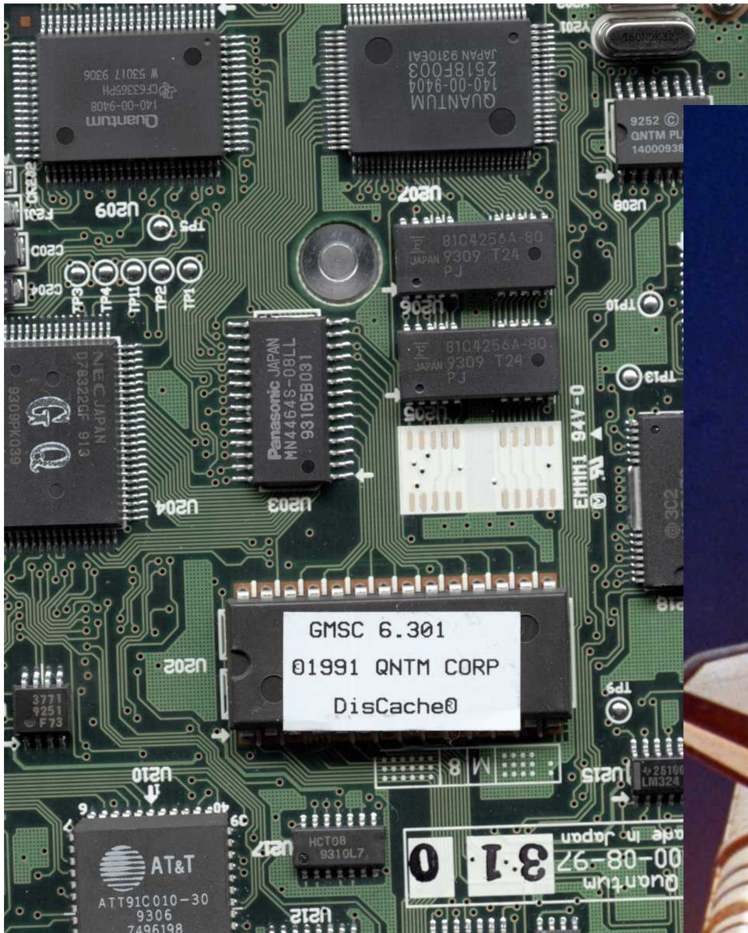
Initial Triggering Action:

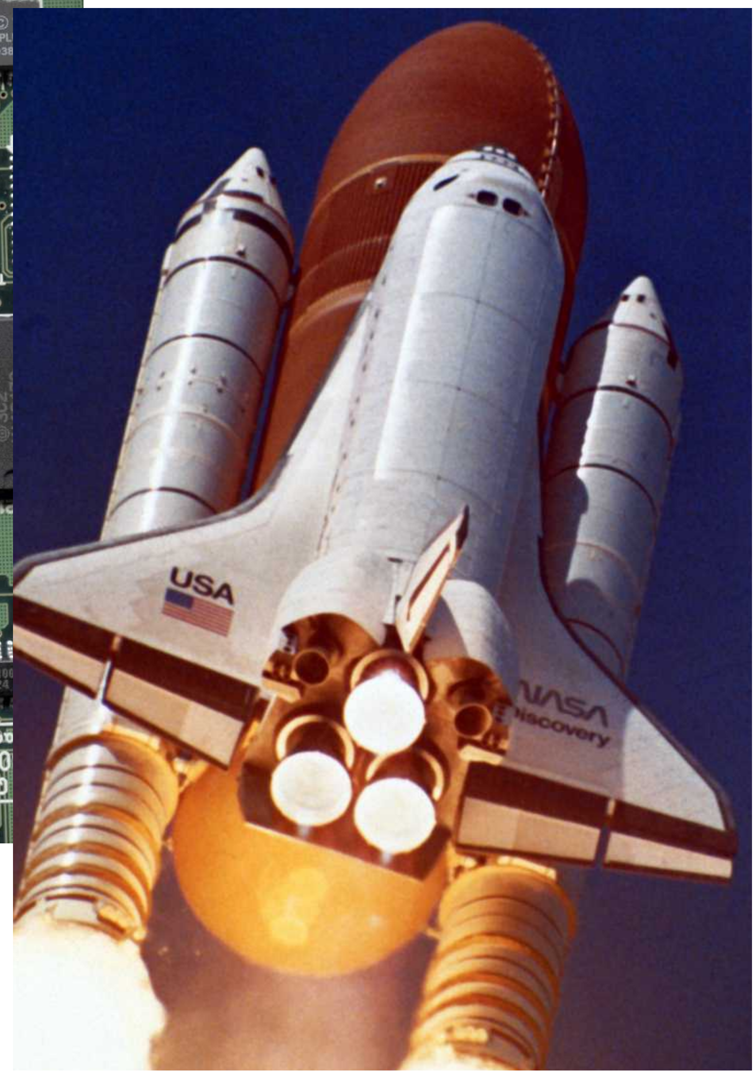
Ion-induced current flows from well contact to substrate contact, and produces a voltage drop within the well, which, in turn, forward biases the parasitic vertical bipolar transistor

Some of Today's Major Radiation Issues for JPL

- **Reduction in DoD activities**
  - Fewer rad hard parts available
  - Less DoD sponsored radiation testing and research
- **Increased COTS parts usage**
  - More unknown process line variations
  - Lot-to-lot, wafer-to-wafer variations in response
  - Parts change rapidly due to competition
- **Increased insertion of emerging technologies**
  - Examples: photonics, microelectromechanical systems (MEMS), system on a chip (SOAC)
  - Small, aggressive flight projects demand high performance and take risks
- **New problems with advances in traditional technologies**
  - Low dose rate sensitivity of linear bipolar parts
  - Scaling effects
  - Effects at low temperature
  - Displacement damage effects
  - Greater total dose sensitivity for some technologies (lower voltages)
  - New single event effects
    - Single event dielectric rupture - permanent effect
    - Proton-induced latchup
    - Single event transients
- **Radiation testing more complex and difficult to interpret**
- **Many more small, low-cost flight projects**
  - Can't afford radiation hardness assurance (RHA) testing, but they need it early in design cycle

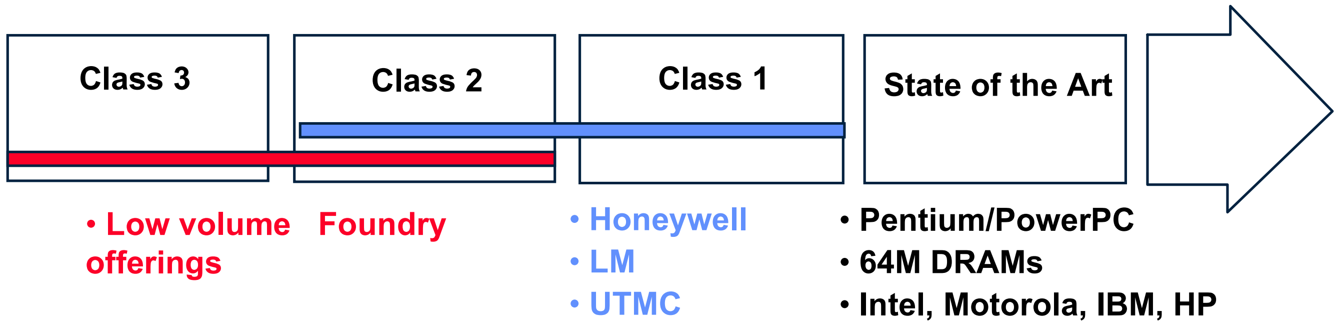
Commercial-off-the-shelf (COTS) parts in space





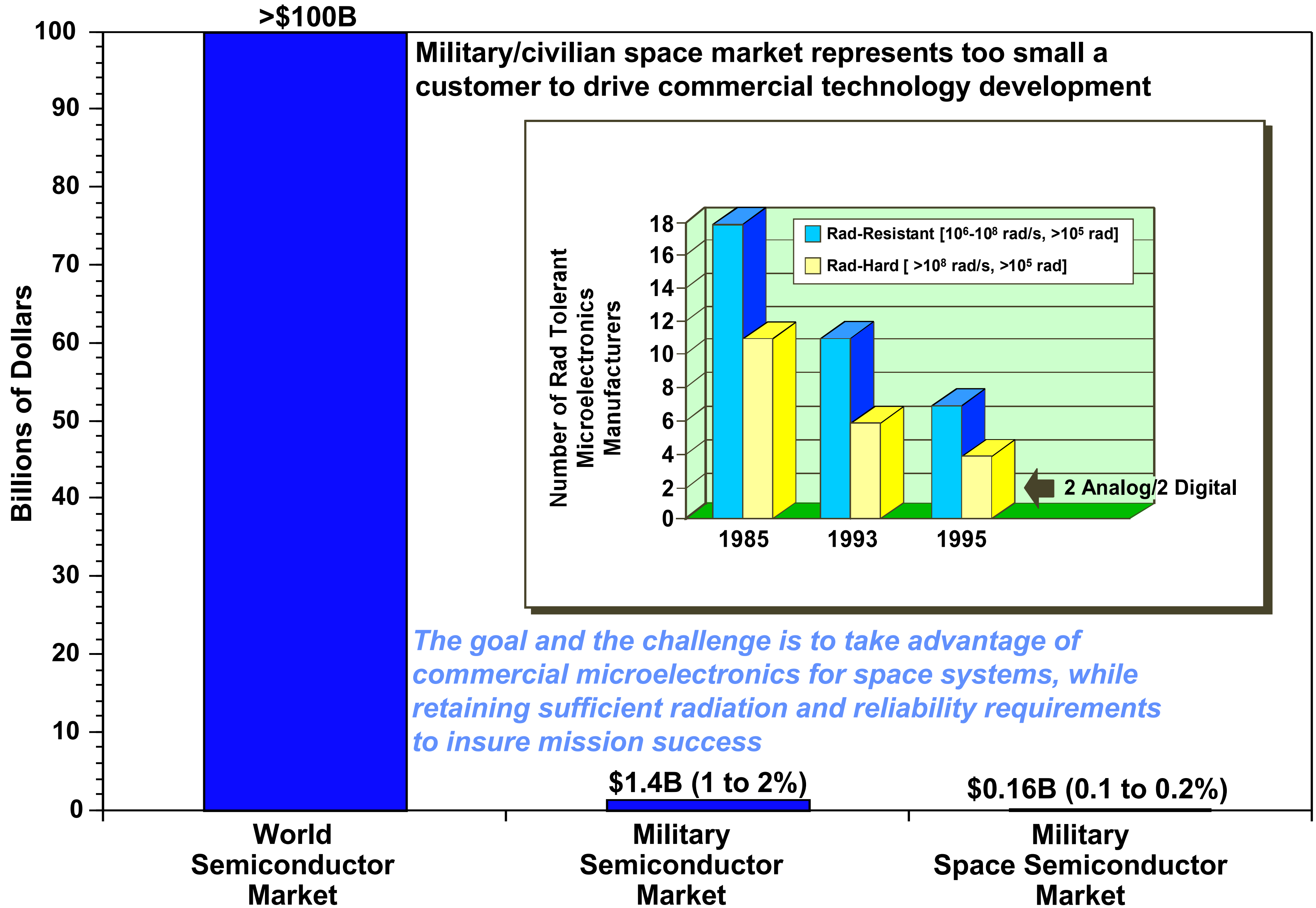
Impetus for COTS Use in Space

- **Access to high performance, state-of-the-art microelectronics - difficult to achieve with small, custom parts purchases**



- **Large, standardized software base**
- **Lower cost**
  - Although upscreening can raise cost substantially
  - Parts are small fraction of total satellite/spacecraft cost (5 to 10%), but this cost will be relatively higher in future
- **Decreased availability of parts off rad-hard processing lines**
- **Greater government reliance on industry standards and specifications for part procurement (Perry Directive)**
- **For JPL, new paradigm of "Better, Faster, Cheaper" allows for risk management rather than complete elimination of risk, and requires quick, inexpensive procurements**

World Semiconductor Device/Circuit Business



Problems with Use of COTS in Space

- **Small customers (space) cannot drive development, specifications or requirements**
- **Life cycle costs can actually be higher for COTS-intensive satellite due to added testing, part and system failure, system re-work, added cost of shielding**
- **Reliability data on COTS is often unknown or unavailable to small customer**
- **Commercial competitiveness to reduce cost, improve performance can jeopardize availability of specific parts required in future systems**
- **Space applications do not usually allow for repair or replacement**
- **Plastic encapsulated microcircuits (PEMs) are very popular and more reliable than previously, but can still pose problems for space use**
  - Handling and assembly problems
  - Encapsulants vary in composition and properties
  - Moisture absorption - “popcorning”
  - Limited temperature ranges
  - Differences in thermal expansion coefficients are a problem with thermal cycling
- ***Radiation is a big problem***

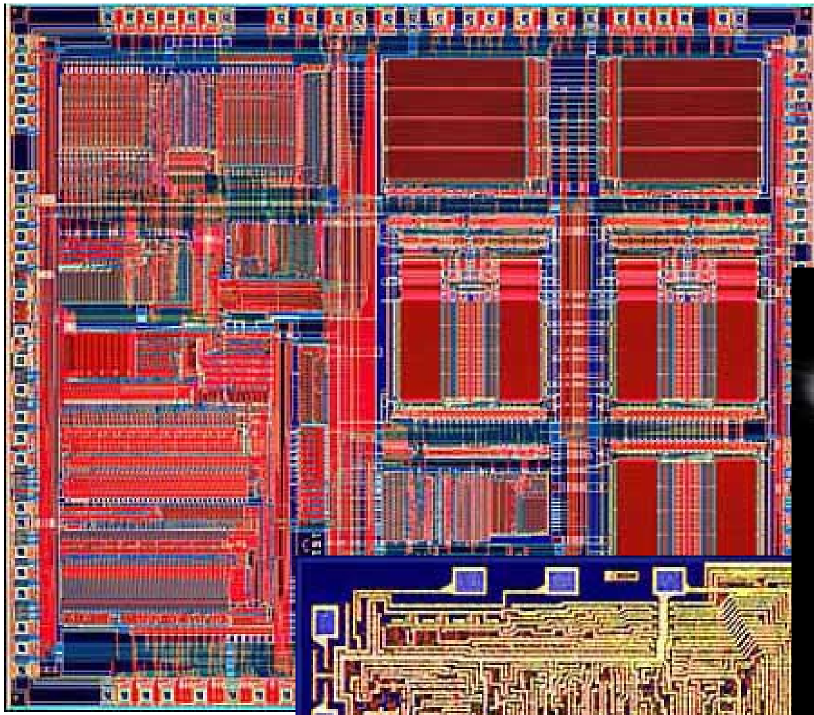
Radiation Complicates COTS Usage

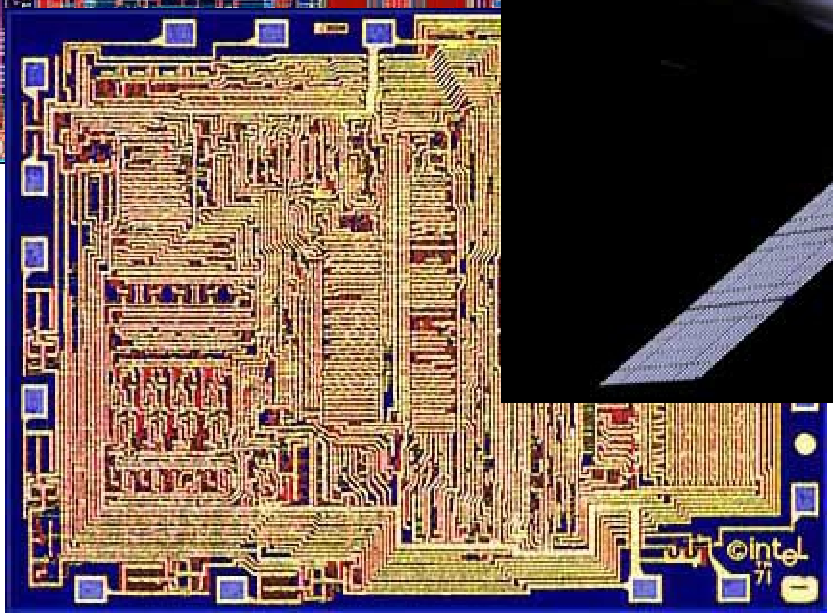
- **Reliability and RHA often unknown**
- **Radiation is unique**
  - Can't leverage off other high rel users like automotive
- **TID response depends on process**
  - "Positive" changes can reduce radiation tolerance
  - NASA technical penetration often difficult
- **SEE depends on circuit design and dimensions**
  - Commercial vendor can change these without notice
- **No good way of predicting radiation response without testing**
  - *IRONY* – Process knowledge, testability and penetration are where you don't need them – rad hard process lines
- **Packaging can make RHA hard to establish**
  - Flip chip bonding
  - SEE hard to do on plastics
  - Multichip modules (MCMs) hard to test

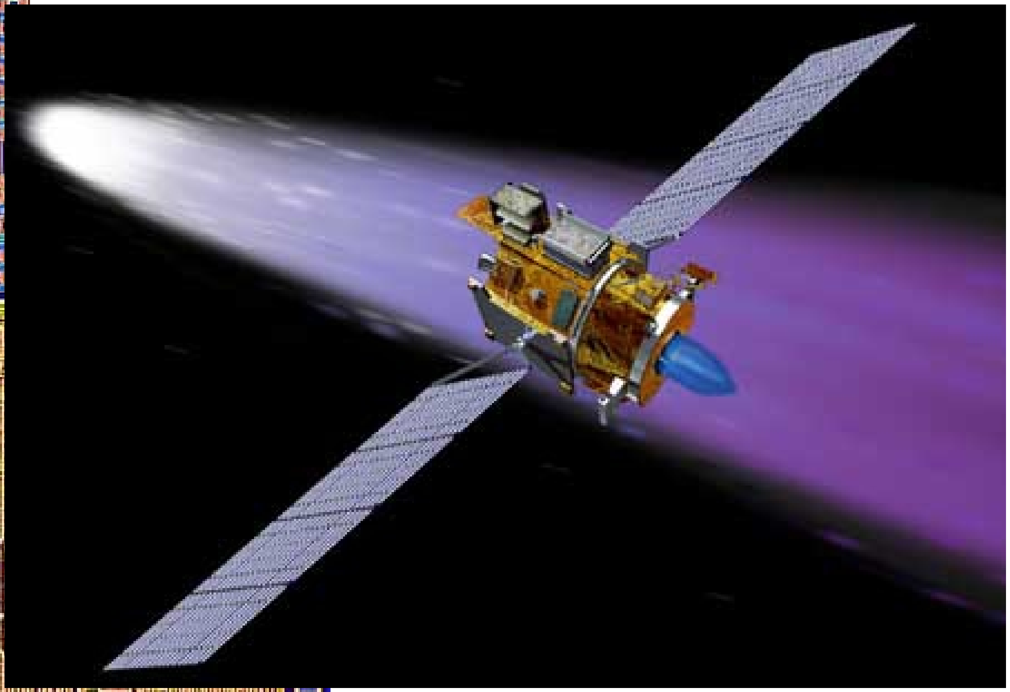
JPL RHA Activities in Support of Advanced COTS Usage

- **Radiation analysis and testing of COTS parts**
  - Support to NASA flight projects
  - Cheaper, easier test methodologies
- **Radiation risk mitigation techniques**
  - Latchup mitigation
    - Circuit solutions
    - Neutron irradiation
  - RadPak, shielding
  - Mitigation of hard errors, dielectric rupture
  - Software mitigation techniques
- **Evaluation, research**
  - Advanced COTS technologies
    - FPGAs, DRAMs, highly scaled devices, MCMs, MEMS, photonics, III-V-based technologies
  - New radiation phenomena
    - Enhanced low dose rate effects
    - FPGA anti-fuse rupture and connection
- **Dissemination of radiation data**
  - Data banks at GSFC, JPL, MSFC (materials), etc.
  - http:\\radnet.jpl.nasa.gov

Enhanced Low Dose Rate (ELDR) Effects in Linear Bipolar Circuits







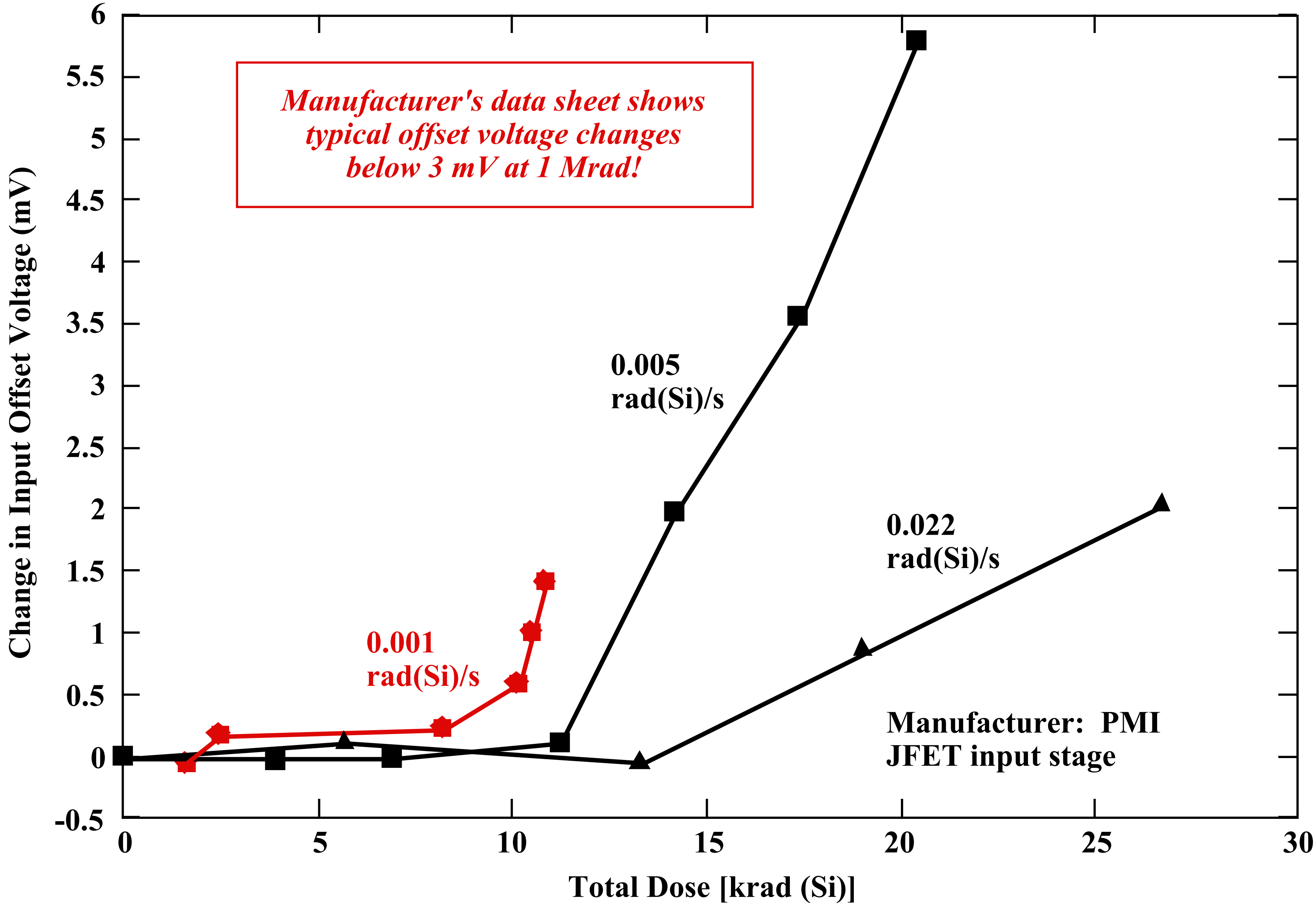
Enhanced Low Dose Rate Effects in Bipolar Circuits

- **Much lower failure dose at low dose rate**
- **Severe radiation hardness assurance (RHA) problem**
  - Opposite behavior of CMOS
  - Typical laboratory radiation test is no longer conservative
  - At this time, there is no RHA test
  - Direct test at low dose rate is time consuming and expensive
    - Prohibitive schedule impact for FBC project
- **Enhanced low dose rate effects are complex**
  - Not observed as frequently in transistors
  - Failure modes can be different than those observed at high dose rate
    - Overtesting at high dose rates is not viable
  - Differences between part types from same line
  - Differences between manufacturers for same part type
  - Effect is related to damage in oxides with low electric fields present
  - Advances have been made in identifying physical model, but still not complete

Space Example - Suspected ELDR Failure in Pressure Transducer

- **Used on Cassini and in numerous Earth-orbiting satellites**
  - 15 year history of all units drifting with time
- **Failures have been observed**
  - Due to gradual drift with time
  - About 7% of units have failed
  - Failures typically occur 1.5 to 2 years after launch
  - Unfortunately, no on-board radiation monitors
- **Consistent with ELDR Failure Mechanism**
  - Would expect gradual drift with time
  - Direction of drift changed when op-amp type was changed
  - Estimated radiation level was approximately 20 krad

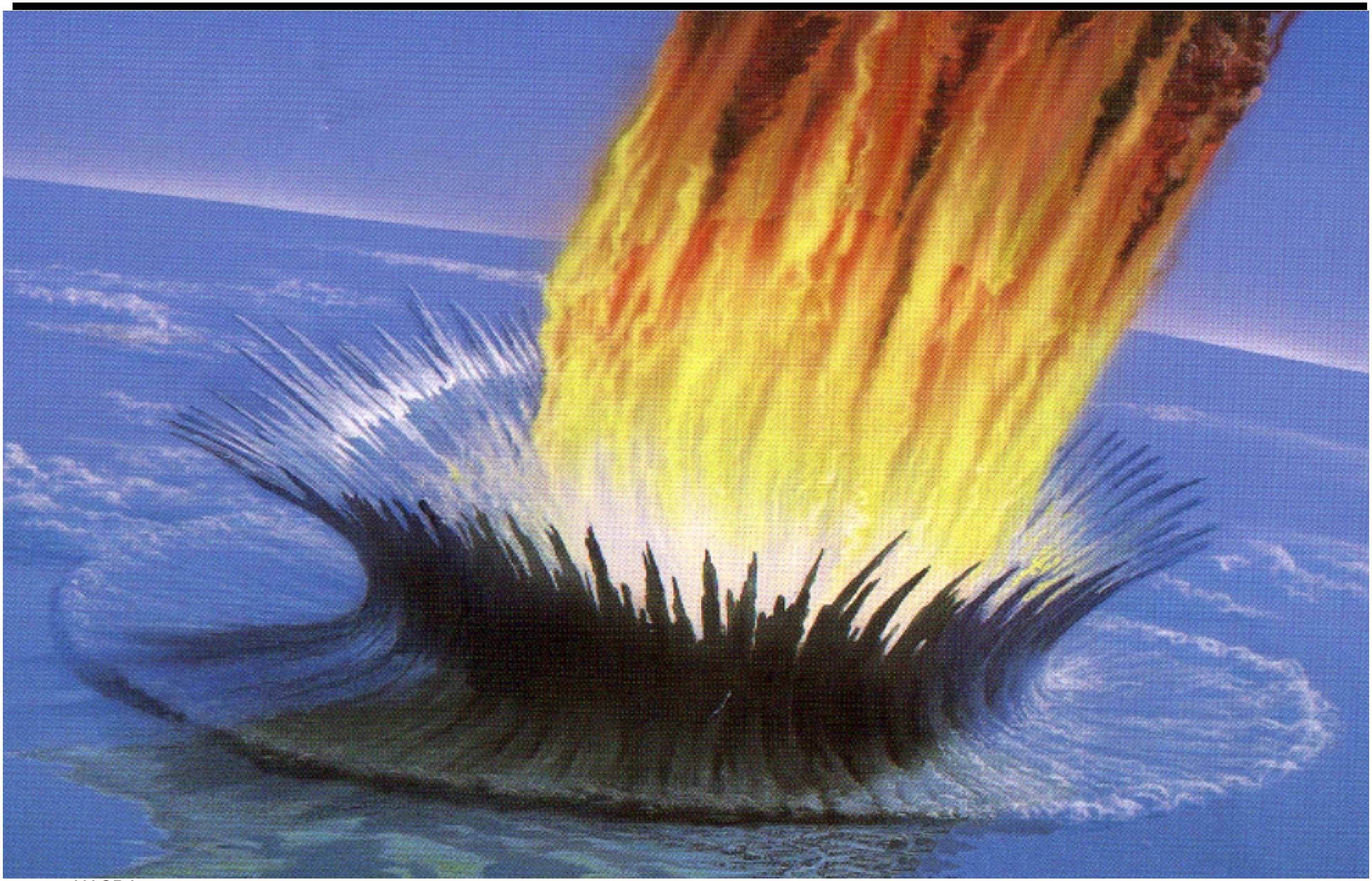
Very Low Dose Rate Effects in OP42 Op-Amp



How Do We Deal With ELDR Problem??

- **Pay careful attention to manufacturer and process for all linear devices**
  - Processing lines are frequently changed
  - Don’t rely on archival data
  - Avoid devices with “super” specifications
- **All linear bipolar devices should be tested at two dose rates**
  - 50 and 0.005 rad(Si)/sec
  - This is not a low dose rate characterization
  - Don’t use any device that shows large degradation under either condition
- **Future Possibilities**
  - Examination of cross section of internal oxide structures
  - Working agreements with specific manufacturers about process control
  - Tests at elevated temperature
    - No single temperature for all parts

Displacement Damage - A “New” Old Problem



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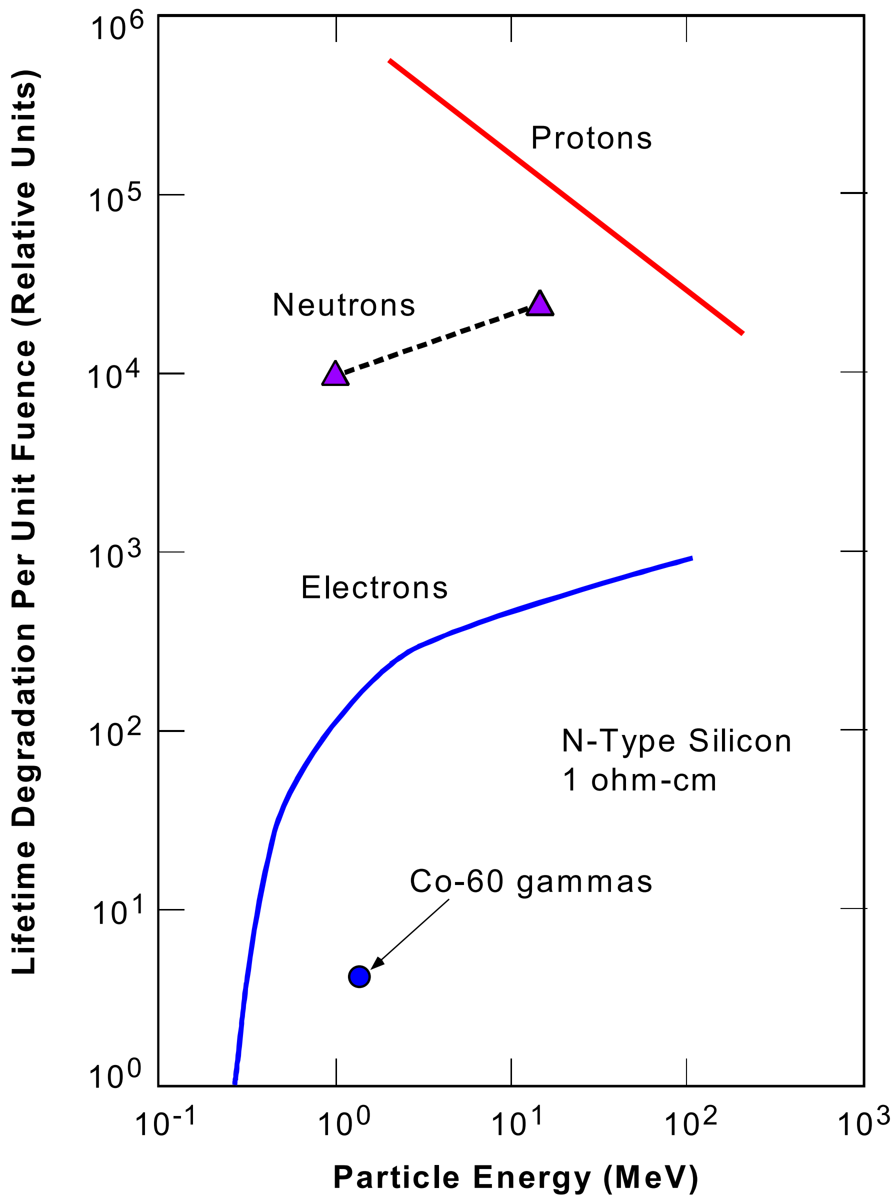
Displacement Damage

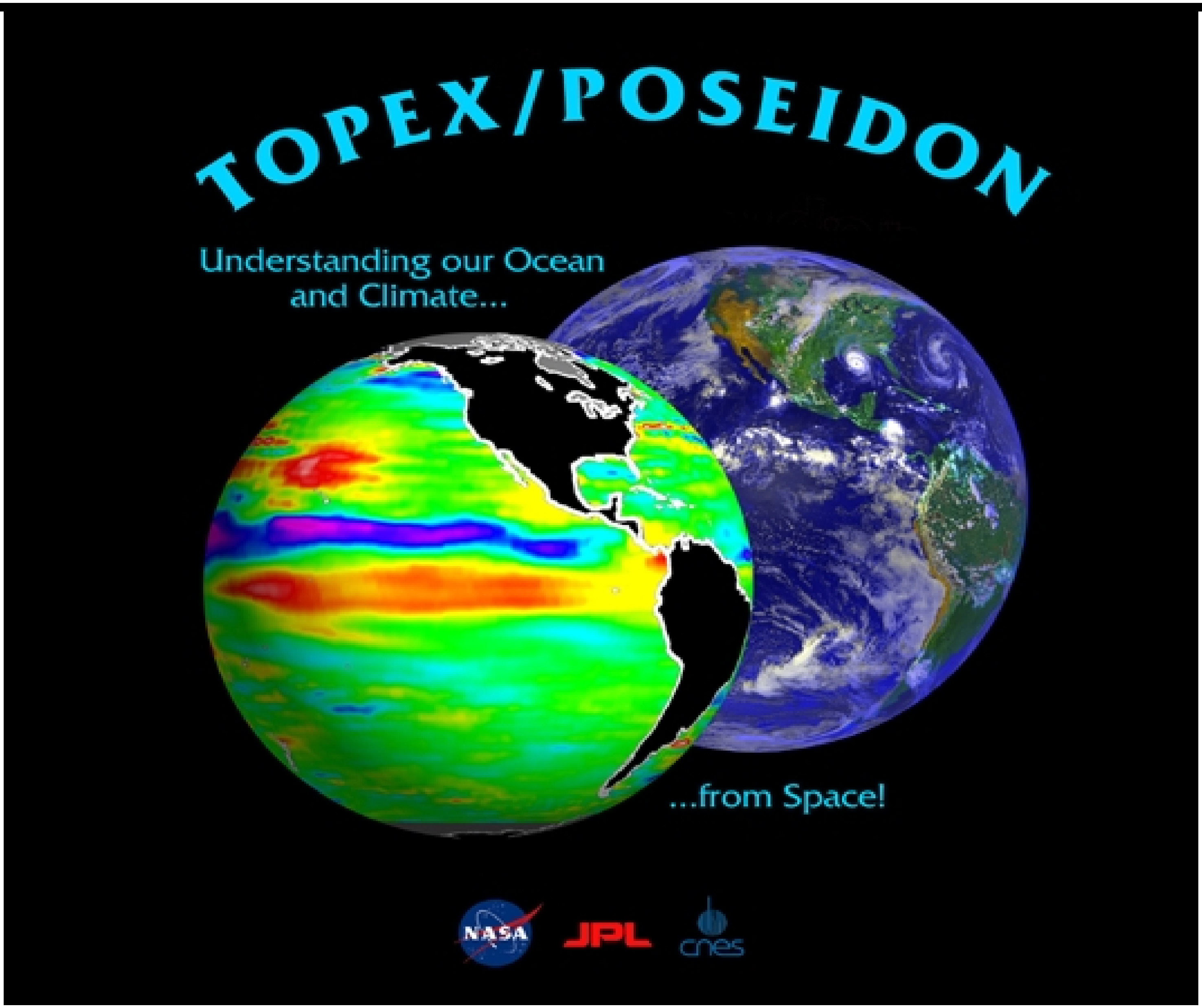
- **Basic change in semiconductor lattice caused by scattering collisions**
  - Leads to alteration of electrical and optical properties
    - Minority carrier lifetime, mobility, absorption edge, electroluminescence, carrier removal (takes lots of fluence)
- **Historically the first "radiation effect"**
- **Over the years, there has been less concern with displacement damage (NASA only)**
  - Very minor effect in CMOS (carrier removal)
  - Usually less important than ionization for discrete transistors
  - Testing is expensive and only done when necessary
- **Why is displacement damage now important??**
  - Increased use of advanced commercial linear bipolar devices
  - High precision, high performance circuit applications
    - Second order effects become important
  - More use of specialized components
    - High precision voltage references
    - Photonic devices
  - Smaller spacecraft
    - Less shielding
    - Lower design margins
    - Nuclear power sources in close proximity

Displacement Damage Effectiveness of Radiation Types



A krad is not always a krad

Displacement Damage in TOPEX/Poseidon Optocouplers



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Thruster Use and Thruster Status Failures on T/P

Thruster	Days after Launch										
	23	35	63	133	231	360	538	647	786	1014	1252
A2-A	ok	ok	–	–	–	–	–	–	–	–	F
A2-B	ok	ok	–	–	–	–	–	–	–	–	F
C3-A	ok	ok	–	–	–	–	–	–	–	–	F
C3-B	ok	ok	–	–	–	–	–	–	–	–	F
A4-A	–	ok	ok	ok	ok	ok	ok	ok	F	F	F
A4-B	–	ok	ok	ok	ok	ok	ok	ok	F	F	F
C4-A	–	ok	ok	ok	ok	ok	ok	ok	ok	ok	F
C4-B	–	ok	ok	ok	ok	ok	ok	ok	F	F	F

First failures occur at 1.4×10^{10} p/cm^2

Notes:
(1) Sixteen thruster pairs were fielded on TOPEX.
(2) Two were never used; the other 14 were all operational early in the mission(≈ day 35)
(3) After day 35, only the 4 pairs above were activated. Thus, there are no data after day 35 for 10 of the 14 pairs that were used early in the mission.
(4) Dashes in the above table indicate that the thruster was not used at that particular time.
(5) Failure have only been observed in the "Thruster Status" application, not in the "Thruster Driver" circuit. Thus, all thrusters are still operational even though the status logic does not function properly.

Optocoupler Applications on TOPEX/Poseidon

- **A variety of circuits use optocouplers, but so far only thruster status circuit has shown failures**

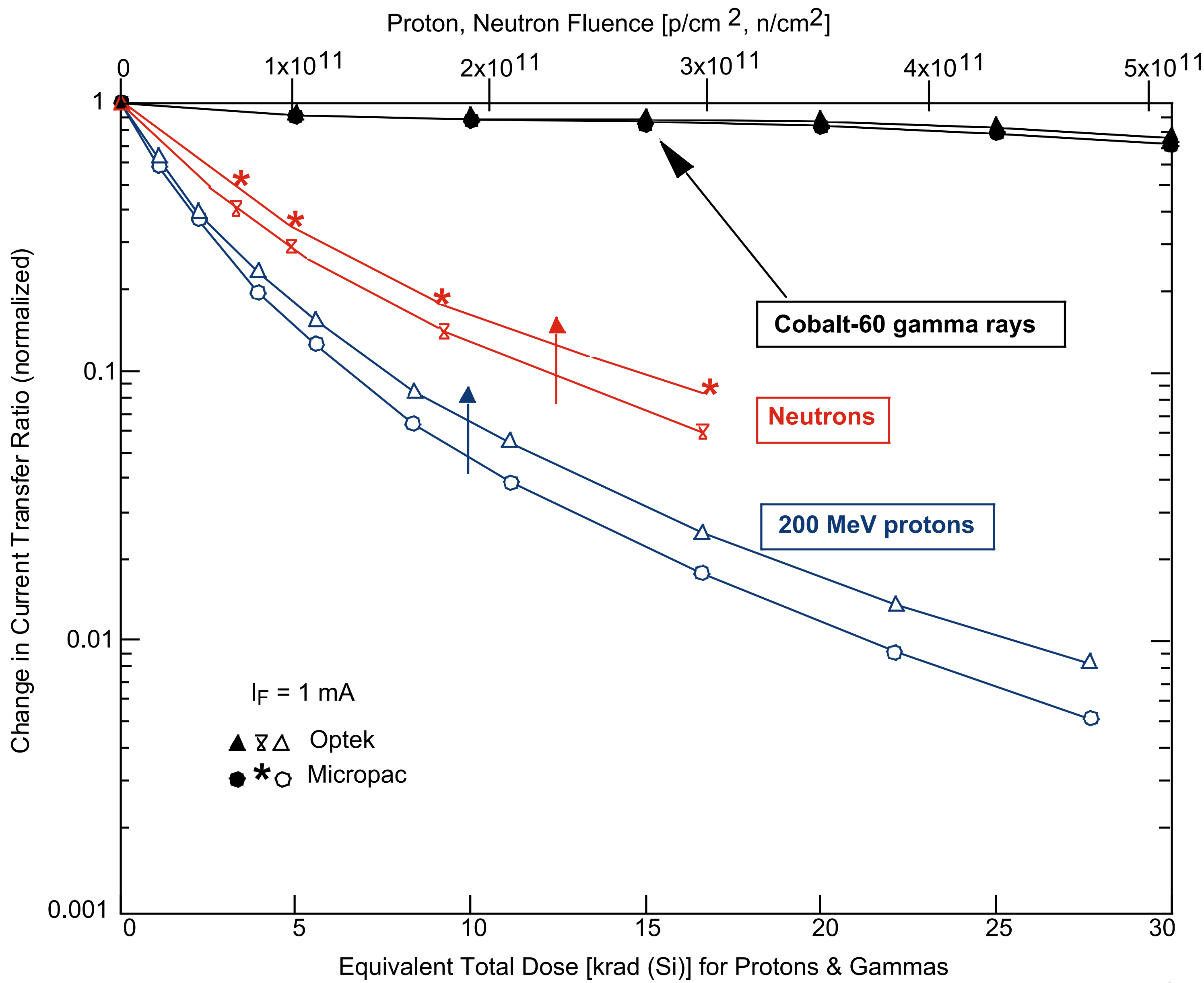
CTR = I(detector)/I(LED)

Circuit	*I_f (mA)*	*Required CTR*
Thruster Actuation	7.8 - 8.3	0.2
Thruster Status*	**0.55**	**0.5**
Heater Driver	7.8 - 8.3	0.2
Latch Valve Driver	7.8 - 8.3	0.2
Reaction Wheel Control	16.8	0.1 - 0.2

*** - Only circuit exhibiting failures to date**

- **Note the combination of low available light emitting diode (LED) current and relatively high required current transfer ratio (CTR)**

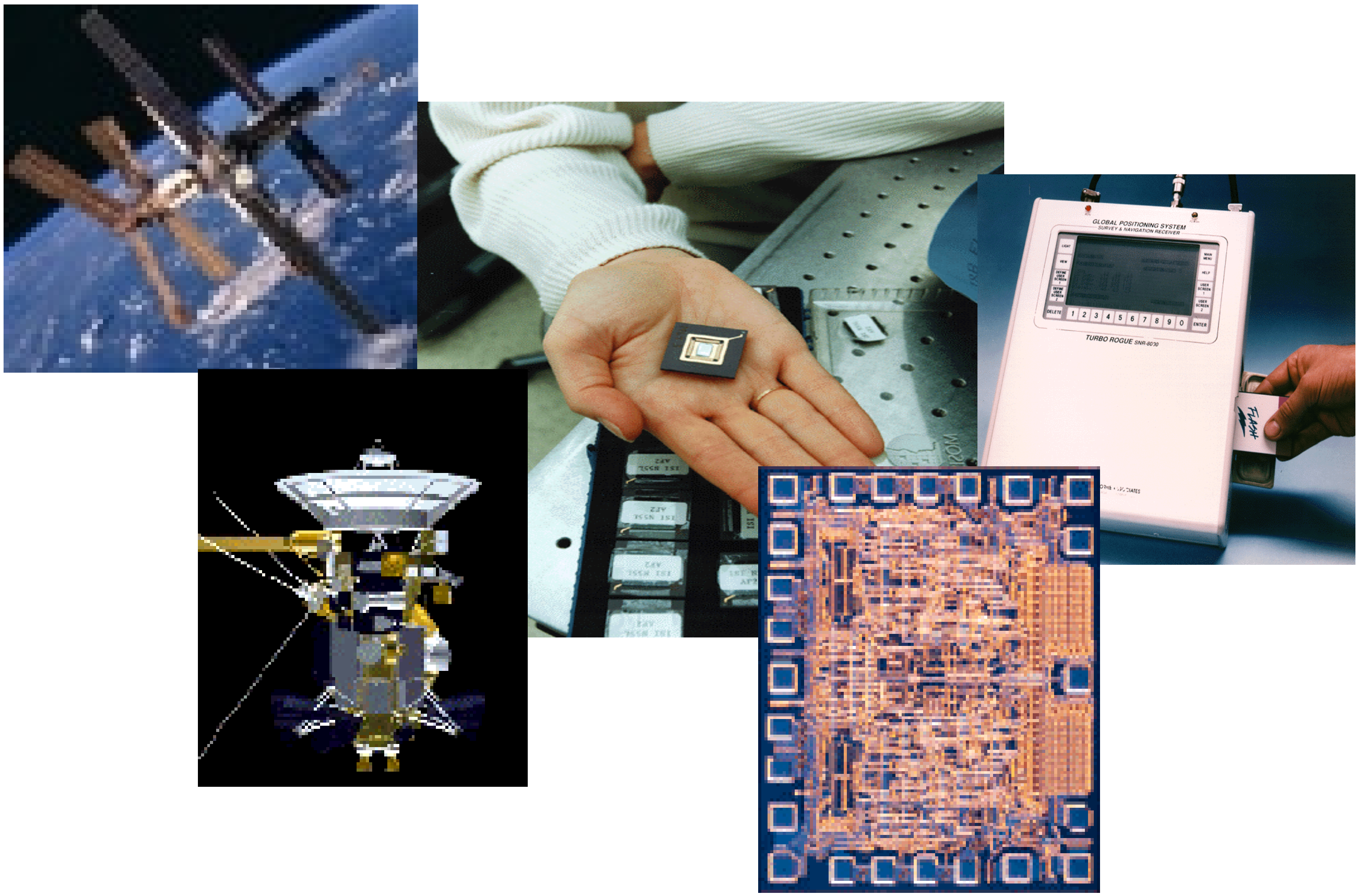
4N49 Degradation from Protons, Gammas, and Neutrons



Optocoupler/Displacement Damage Summary

- **On T/P, expect to see additional optocoupler failures in thruster command electronics after 8 years in orbit**
  - For greater hardness assurance, optocoupler applications should use high input current and low CTR
  - Best solution is to use couplers that employ harder LEDs and non-Si detectors
- **Displacement damage effects must be dealt with separately from total dose and corresponding Co-60 testing**
  - Separate requirement for displacement damage often not given
  - People are used to thinking in terms of “dose”, whether its protons, electrons or Co-60 gamma rays that are used for testing
  - Missions with significant proton (and/or neutron) fluences must address displacement damage effects in photonic devices and sensitive linear circuits
- **Displacement damage hardness assurance for NASA is also difficult because of complicated energy dependence of proton displacement damage**
- **For optocouplers, temperature effects also need to be folded into assurance assessments**
- **Must also consider neutron displacement damage in NASA missions with RTGs like Cassini**

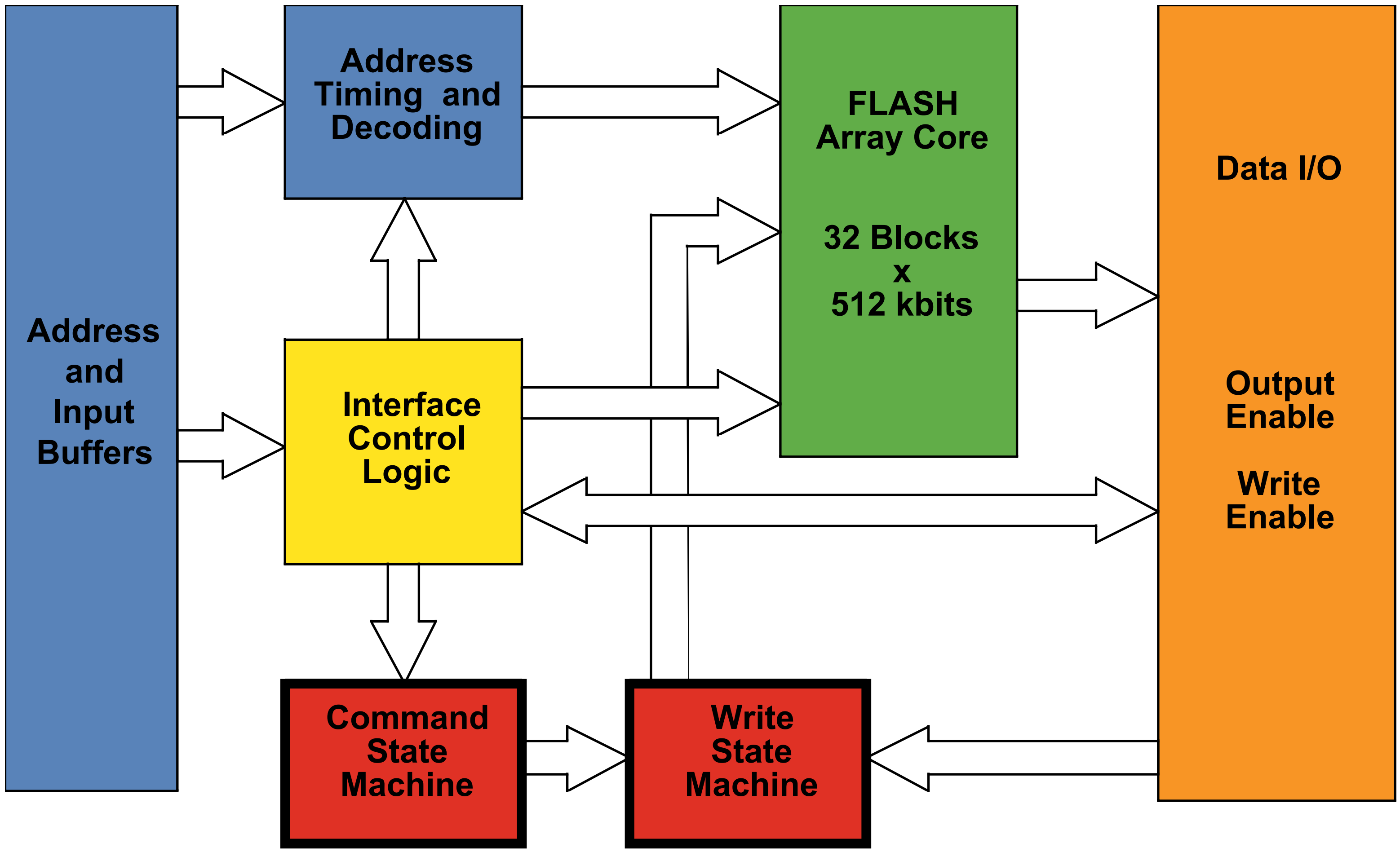
Flash Memories



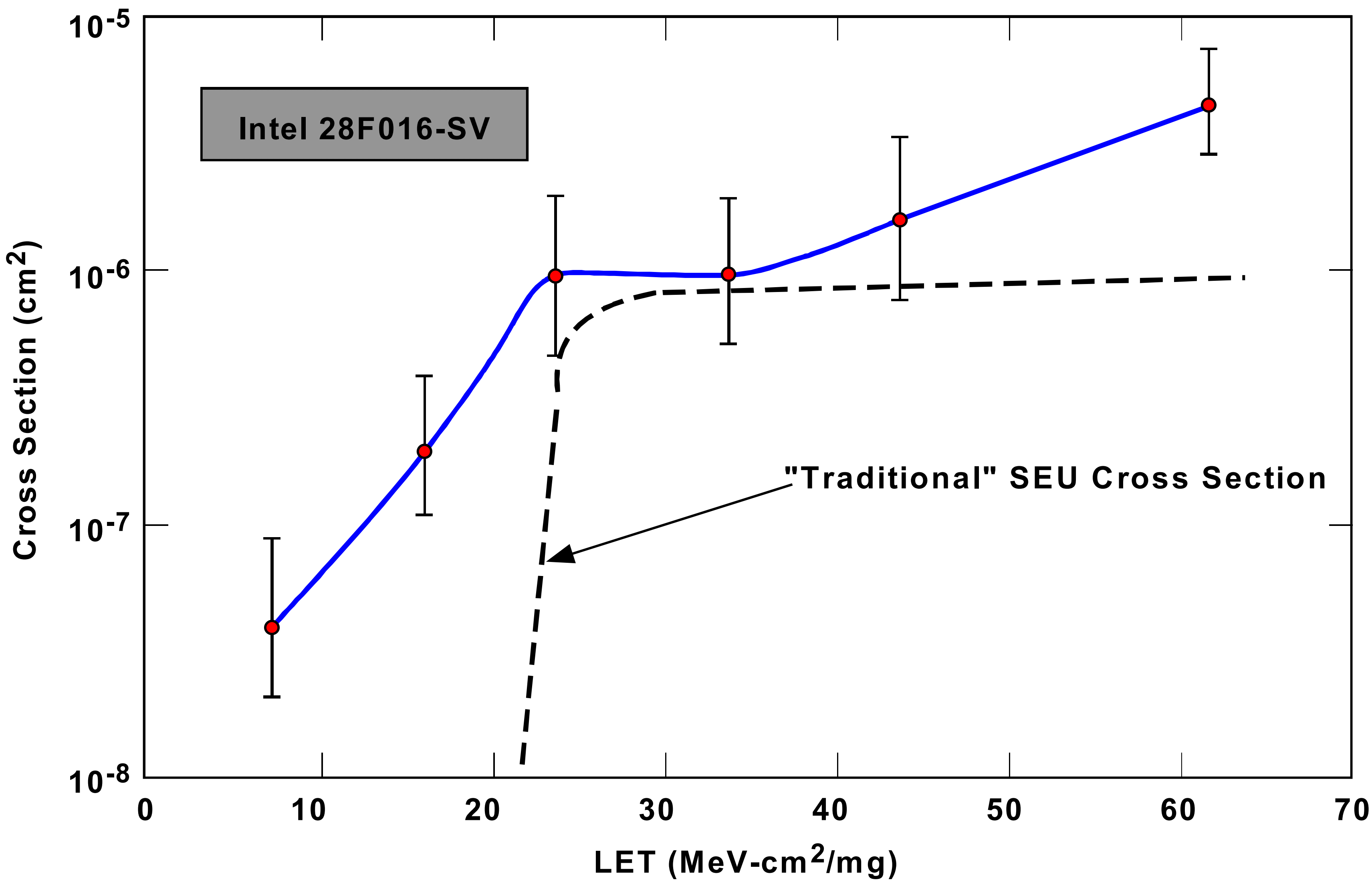
Flash Memories

- **Strong interest from JPL projects**
  - “Read-mostly” mode fits with many applications
  - Some applications mainly unpowered - also suitable
- **Flash technology**
  - High internal voltage required to write, erase
  - Requires thicker gate oxides in some regions
  - Very complex circuit architectures
    - Charge stored in insulator sandwich
    - Slow writing process
    - Block read and write modes to increase speed
  - Different cell technologies used
- **Operating modes**
  - Write
  - Read
  - Standby
  - Off
- **Radiation concerns**
  - Single event upset
  - Stuck bits
  - Total dose degradation

Block Diagram of Intel 28F016 Flash Memory



Cross Section for Complex Functional Upset Modes in Flash Memory



Functional Error Modes Observed for 28F016SV Flash Memory

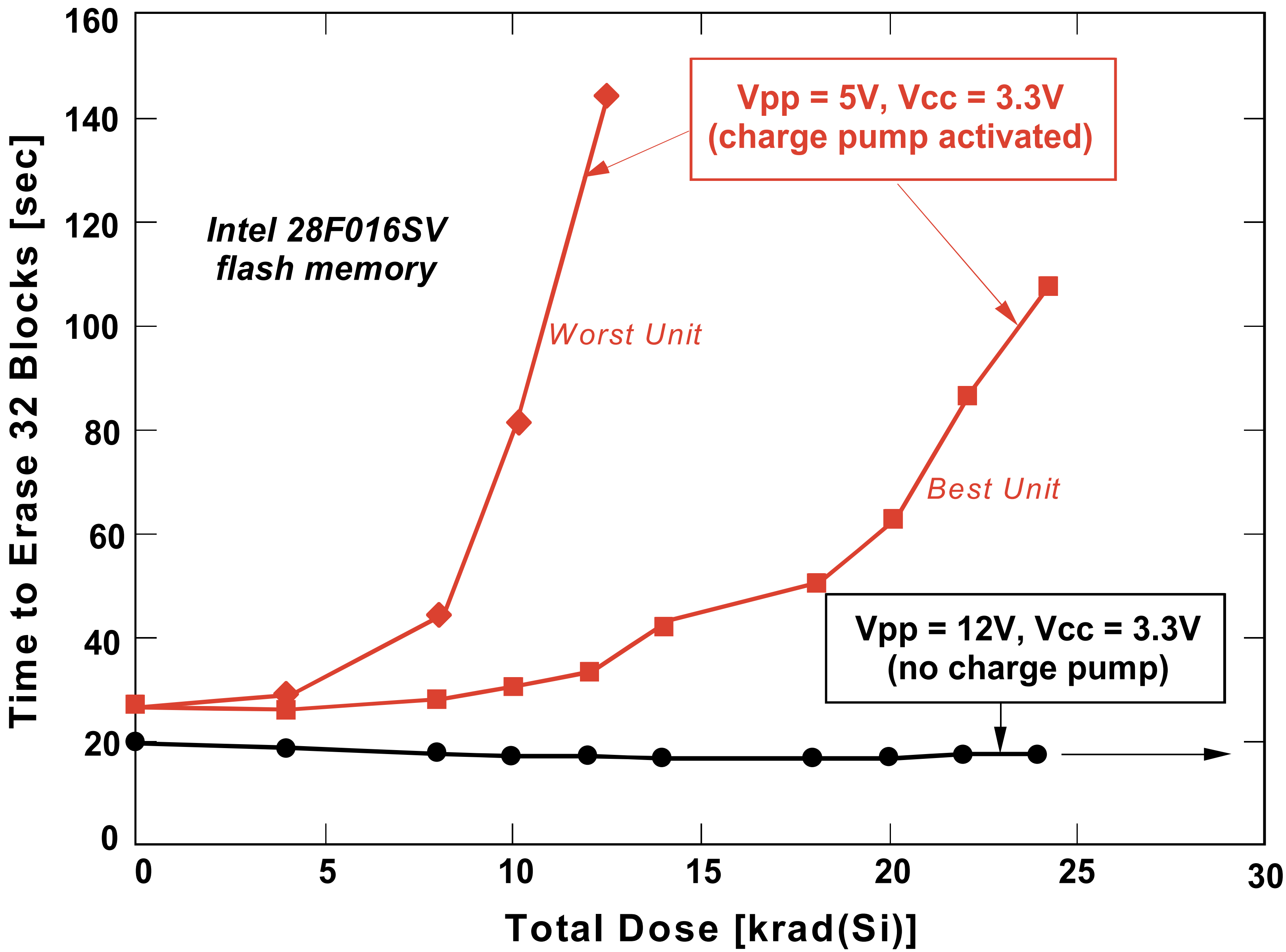
Error Type	Description	Recovery Method
Block clear lockup	Block clear complete status never appears	Power-cycling
False block clear	One or more blocks show block clear, even though they are not cleared	Power-cycling
Slow block clear	Many passes are required to establish block clear	Wait (power cycling not req)
Row/column changes	Large portions of the memory array change state within a short time period, accompanied by block clear lockup	Power cycling
Slow first add. prog.	After successful block clear, first address takes many passes. Subsequent addresses work OK	Wait
Read lockup	Status bits indicate internal modes and instructions are active, when device is expected to be in the ready state	Power cycling
Write lockup	DATA WRITE status bit stuck in write-error mode	Power cycling

In many advanced circuits, traditional SEU will not be the main problem

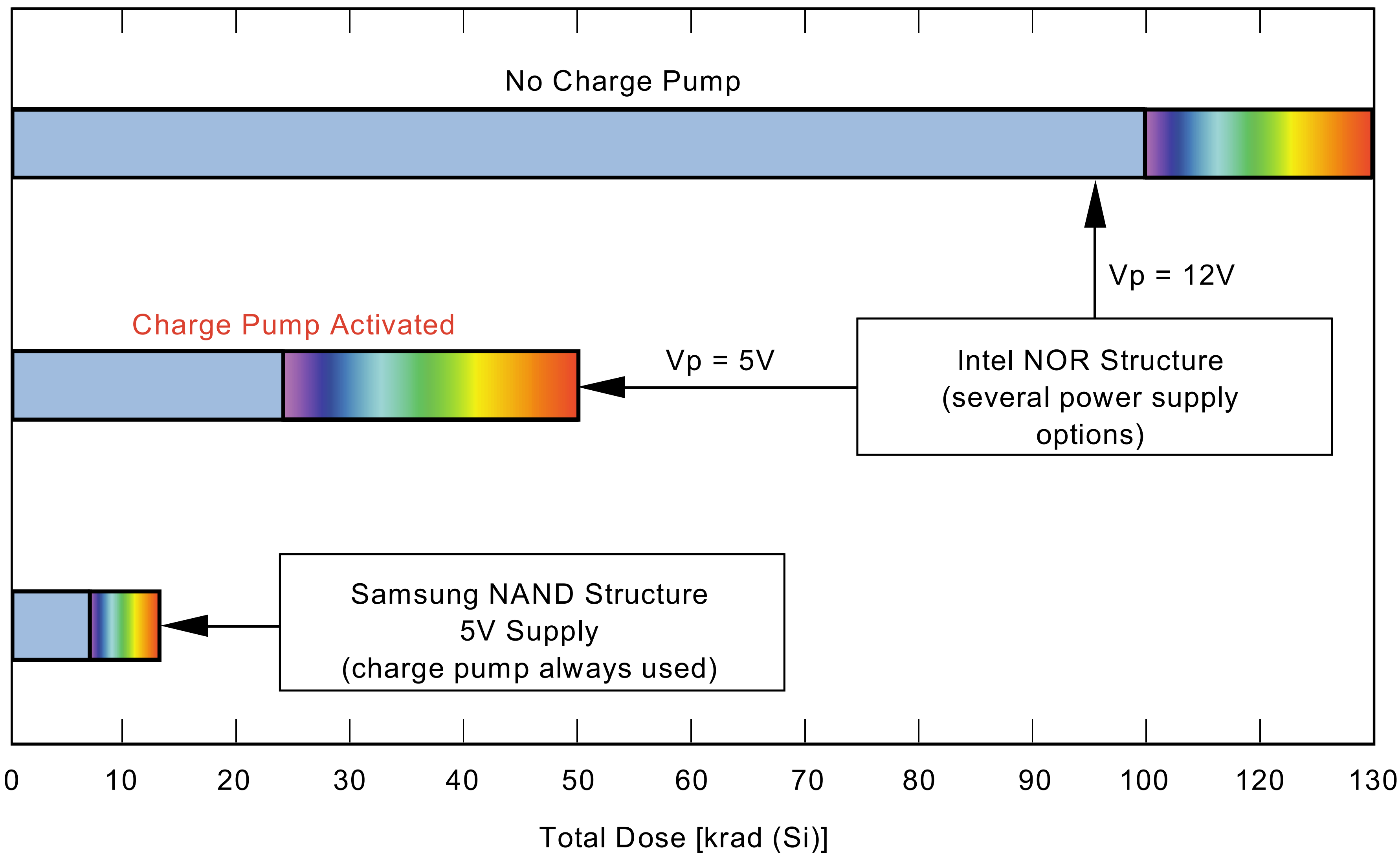
Interference Between Single-Event and Total Dose Effects

- **High test fluences required for thorough SEE characterization**
  - Fluences on the order of 10^7 ions/cm^2 can cause total dose degradation in commercial parts
- **Total dose damage can confuse results**
  - May appear to be “stuck bits”
  - Inconsistent test results
- **Charge pump circuits can dramatically alter SEE and TID response**
  - Higher internal voltages mean thicker oxides and more TID sensitivity
  - TID can cause charge pump turn-on delay and current excursions that can be missed in testing

Time to Erase 32 Blocks with Two Different Programming Voltages



Total Dose Failure Levels in Flash Memories

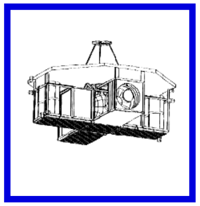


Summary of Flash Memory Results

- **Upsets dominated by controller errors**
  - Individual cell upsets in array are not a significant problem
  - Complex functional errors occur
  - Write errors during read mode
  - Difficult to use conventional EDAC
  - Cross section remains small
- **Large currents sometimes occur during tests**
  - Not always associated with functional errors
  - Persist after irradiation
- **Hard errors not a significant problem for 32-Mbit and 64-Mbit memories tested**
  - Conflicts with earlier results
- **Total dose results can be complicated and can occur during SEE testing resulting in misleading data**
- **Technology is evolving rapidly**
  - Error modes and cross sections may change

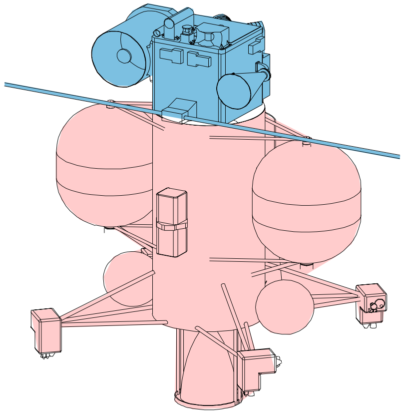
Future Trends, Summary

“Thinking S/C”



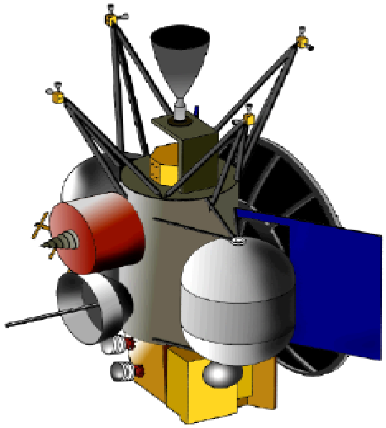
Evolvable HW
Upgradable SW

“X2000”



Reconfigurable HW
Upgradable SW

“Sciencecraft ‘96”



Fixed HW Design
Upgradable SW

“Galileo”

Fixed HW Design
Fixed SW Design

80’s — State of Art — 2002 — Future

SEE and TID Scaling Effects

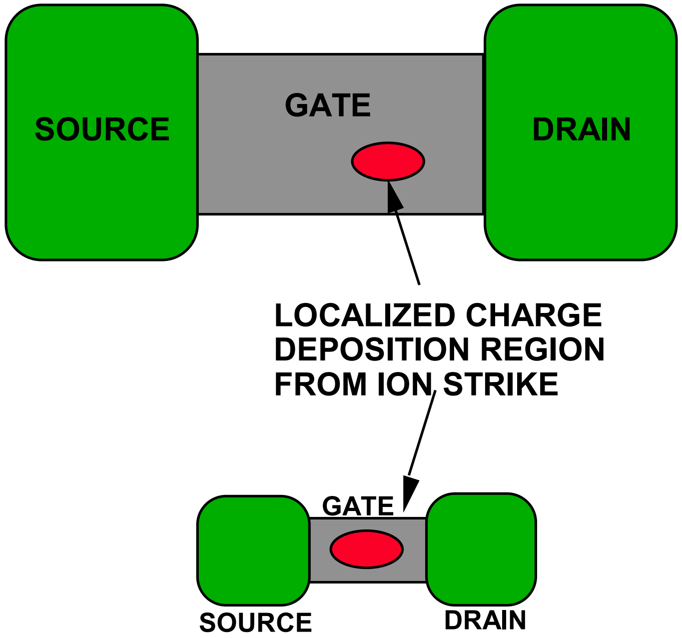
- **New, advanced devices with reduced feature sizes will be more susceptible to both TID and SEE effects**
- **TID effects will be enhanced by lower voltage operation and increased field oxide problems**
- **Smaller feature size often accompanied by thinner epitaxial layers which can enhance latchup susceptibility**
  - Latchup will be difficult to predict
- **Scaling to smaller feature size will enhance SEU rates for many technologies**
- **Permanent, single particle-induced hard errors, similar to gate rupture in power devices, will increase with scaling**
  - Greater electric field strength enhances hard errors
  - Effects demonstrated for DRAMs, FPGAs
- **At small feature sizes, a single particle can cause TID “microdose” failure in a single transistor**

Permanent Single Particle – Induced Errors in Scaled Devices

OLDER DEVICES

LOCALIZED DAMAGE REGION << GATE AREA

LARGE NUMBERS OF IONS MUST STRIKE GATE TO CAUSE TOTAL DOSE DAMAGE



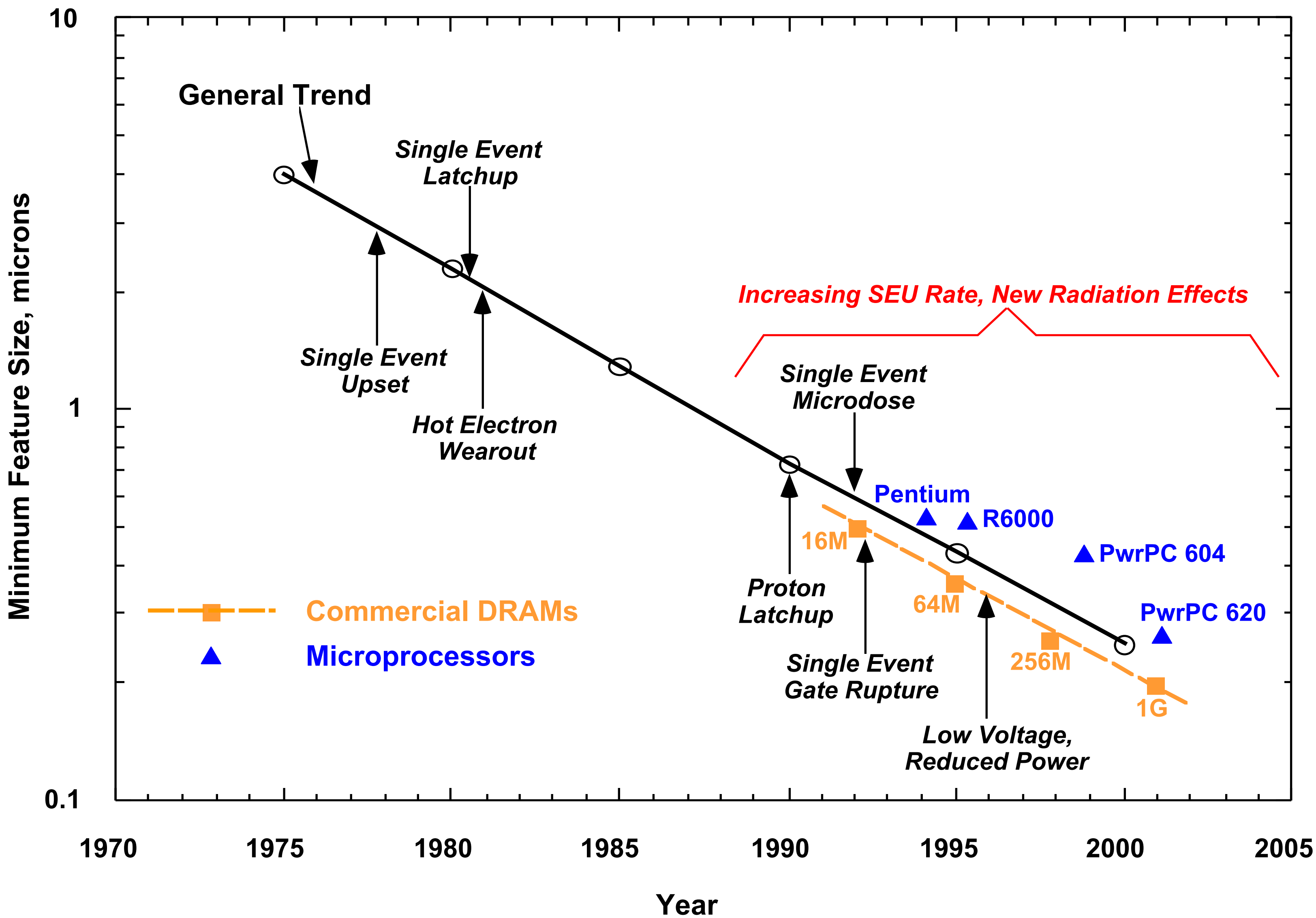
SCALED DEVICES

LOCALIZED DAMAGE REGION ≅ GATE AREA

SINGLE ION STRIKING GATE CAN CAUSE TOTAL DOSE FAILURE

Feature Size/Radiation Effects Trends in Microelectronics

JPL
Electronic
Parts
Engineering



Note increasing radiation vulnerability with decreasing feature size

NASDA

Radiation Issues - Into the Future

- **Several trends will require a robust radiation test and analysis program to insure low mission risk**
  - Increased usage of new, emerging technologies
  - Further decreases in availability of radiation hardened parts
  - Increased usage of commercial off-the-shelf (COTS) parts in space systems
    - Rapid evolution of COTS parts due to commercial competition requires frequent testing
- **Because of crowding at LEO altitudes, and the large number of satellites required to give complete earth coverage at LEO, there will be a trend to use higher altitudes in the Van Allen belts resulting in much higher radiation requirements**
- **MEMS will proliferate and offer a variety of sensor and actuator techniques, many of which will exhibit radiation sensitivities**
- **Highly autonomous spacecraft will perform extensive on-board processing at high data rates requiring optical computing and data transfer systems with unknown radiation response**
- **Systems will become available that incorporate digital, photonic and microwave devices fabricated from different material families all on one substrate - system-on-a-chip (SOAC)**
  - Structure complexities including stresses at material interfaces will lead to radiation susceptibility

Summary - Some Radiation Design "Rules of Thumb"

- **COTS parts usage requires care and probably rad testing - select judiciously and be wary of archival data because radiation response can change quickly**
  - Use only hybrids where you can discover what's inside
- **Use hardened parts for core engineering systems, such as flight computers**
  - Honeywell, Lockheed-Martin, Sandia
  - Hardened static RAM for computer memory
- **Linear bipolar parts (op amps, comparators, voltage regulators, etc.) must be selected with care because of enhanced low dose rate effect**
  - Examine input and output circuitry for vulnerable circuit elements - lateral PNPs
  - Some manufacturers worse than others - National parts show strong effect
- **Analog to digital converters are a big problem - select with care - use all CMOS with hardened oxides if possible**
  - Several possible failure mechanisms with BiCMOS A to Ds (and also other BiCMOS parts)
- **Select power MOSFETs with high enough voltage ratings that will allow derating for single event burnout**

Summary - Some Radiation Design "Rules of Thumb"

- **Avoid parts that exhibit single event latchup**
  - For many applications, this is the only high risk radiation issue
  - Can't count on automatic latchup immunity with epi layers
- **In high speed applications, check to be sure that SETs aren't a problem**
- **If power and Si real estate aren't strongly restricted, consider design mitigation of SEE**
- **In advanced, complex parts like flash memories make sure that SEE tests have revealed all types of SEU phenomena**
- **If mission will use solid state memory, selection of mass memory will be a problem - need to avoid proton SEU sensitivity if possible, but most DRAMs are sensitive**
- **For fiber optic links, do not use first window (850 nm) - use second (1300 nm) or third (1550 nm) window links**
  - Fibers and detectors better at longer wavelengths
- **Don't use optocouplers that contain phototransistors - use those with photodiodes**
- **Avoid Si detectors - use III-V detectors**
- **For LEDs, laser diodes and optocouplers, beware of passive optical media (lenses, epoxies) in light path within the device**